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MEASUREMENTS OF THE MELTING CURVE OF PURE He^3 BELOW THE MINIMUM*

J. L. Baum, D. F. Brewer,† J. G. Daunt, and D. O. Edwards
Department of Physics and Astronomy, Ohio State University, Columbus, Ohio
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We have measured the melting curve of pure He^3 in the temperature range 0.12°K to 0.7°K by observing the pressure and temperature of a constant volume containing the liquid and solid phases in equilibrium. The constant volume vessel was filled at 1.2°K with liquid He^3 under pressure[1] through a 0.3-mm i.d. capillary. On cooling this system by means of a paramagnetic salt thermally attached to it,[2] a solid block was created in the capillary thereby sealing the vessel from effects of pressure change above the block and maintaining a constant volume below the block. During further cooling, two phases existed in the vessel. By appropriate adjustment of the initial conditions, the two-phase equilibrium could be maintained over the whole region of observation.

The temperature of the vessel was observed by use of a spherical cerium magnesium nitrate magnetic thermometer thermally attached to the vessel, as has been used and described by us previously.[2] Temperatures could be measured to better than ±0.004°K. The pressure inside the vessel was observed by a strain gauge (Baldwin *SR4*) which was cemented to the cylindrical thin outside wall of the vessel.[3] To minimize possible effects of temperature changes on the strain gauge readings, an identical gauge was used as a compensator, this "dummy" being mounted on a thick unstrained portion of the vessel. The gauge was calibrated when the vessel was filled with liquid He^3 against a calibrated Bourdon gauge, accurate to ±0.1 atmos, located in the He^3 line at room temperature. The strain gauge permitted pressure differences to be read to ±0.02 atmos. Details concerning the use of these strain gauges as pressure transducers at these low temperatures and concerning the high-sensitivity ac resistance bridge for use with them will be given elsewhere. The vessel itself had a volume of 0.3 cm^3 and was constructed to have a large copper internal surface, so as to effect optimum contact between it and the He^3 it contained.

The results obtained during repeated coolings and warmings of the vessel on five different runs are shown in Fig. 1. The scatter in the results of each run is rather small, but systematic

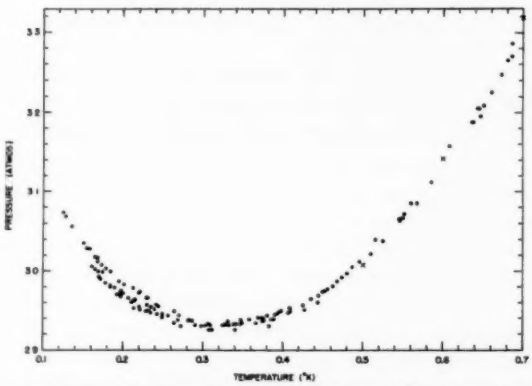

FIG. 1. The melting curve of He^3. The circles give the experimental results reported in this Letter. The crosses are obtained from previous work by Weinstock, Abraham, and Osborne (see text) and represent a few of their results of measurement above 0.32°K.

Table I. The melting pressure of He^3 as a function of temperature. Smoothed values taken from Fig. 1.

T (°K)	0.12	0.14	0.16	0.18	0.20	0.25	0.30	0.40	0.50	0.60	0.70
P (atmos)	30.8	30.5	30.2	30.0	29.8	29.5	29.3	29.4$_5$	30.15	31.4	33.1

errors appear between runs, due to inaccuracies in the Bourdon gauge, which increase the overall error to about ±0.1 atmos. Table I gives smoothed values of the melting pressure taken from Fig. 1.

The measurements above 0.32°K agree within the estimated error with the measurements of Weinstock, Abraham, and Osborne.[4] For comparison we include in Fig. 1 some of these previous results, shown by the crosses, calculated from the equation given by Weinstock et al. At lower temperatures the curve shows an upward trend, the minimum occurring at about 0.32°K and 29.3 atmos, thus confirming directly the conclusions concerning the existence of a minimum arrived at by Fairbank and Walters.[5] Our evaluation of T_{min} agrees closely with that obtained by Lee, Fairbank, and Walker.[6]

These results may be compared with the theories of Pomeranchuk,[7] Sanikidze,[8] and Bernardes and Primakoff.[9] All of these theories predict a minimum, but with subsequent rises in pressure at temperatures below the minimum which exceed our experimental observations. A revised form[10] of the paper by Bernardes and Primakoff shows close agreement with our experimental data, giving a minimum at 0.37°K and rising to 31.3 atmos at 0.12°K. The latter figure is to be compared with our observed value of 30.8 atmos at the same temperature.

We wish to thank the National Science Foundation for a Grant-in-Aid of this research and the Office of Naval Research for assistance towards some phases of the work.

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†On leave of absence from a Nuffield Foundation Research Fellowship held at the Clarendon Laboratory, Oxford University, Oxford, England.

[1]The He^3 was kindly lent to us by the Stable Isotopes Division of the U. S. Atomic Energy Commission.

[2]Brewer, Sreedhar, Kramers, and Daunt, Phys. Rev. 110, 282 (1958); Brewer, Daunt, and Sreedhar, Phys. Rev. (to be published).

[3]We are indebted to Dr. R. M. McClintock for informing us of his experimental work on the use of strain gauges at liquid helium temperatures and for a preprint from the Cryogenic Engineering Laboratory, National Bureau of Standards, Boulder, Colorado, by him describing this work.

[4]Weinstock, Abraham, and Osborne, Phys. Rev. 85, 158 (1952).

[5]W. M. Fairbank and G. K. Walters, Symposium on Liquid and Solid He^3 (Ohio State University Press, Columbus, 1957), p. 220; and Bull. Am. Phys. Soc. 2, 183 (1957).

[6]Lee, Fairbank, and Walker, Bull. Am. Phys. Soc. 4, 239 (1959).

[7]I. Pomeranchuk, J. Exptl. Theoret. Phys. U.S.S.R. 20, 919 (1950).

[8]D. G. Sanikidze, J. Exptl. Theoret. Phys. U.S.S.R. 35, 279 (1958) [translation: Soviet Phys. JETP 8, 192 (1959)].

[9]N. Bernardes and H. Primakoff, Phys. Rev. Letters 2, 502 (1959).

[10]N. Bernardes and H. Primakoff, this issue [Phys. Rev. Letters 3, 144 (1959)]. We are grateful to Dr. Bernardes for communicating his results to us before publication.

FINE STRUCTURE IN THE DECLINE OF THE FERROMAGNETIC RESONANCE ABSORPTION WITH INCREASING POWER LEVEL

E. Schlömann
Research Division, Raytheon Company, Waltham, Massachusetts

and

J. J. Green*
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts
(Received July 7, 1959)

Careful measurements of the resonance absorption as a function of power level on single crystals of yttrium and gadolinium garnet have shown that the saturation curve exhibits a fine structure, which appears as a series of kinks superimposed on the general decline of the absorption with increasing power level. The measurements were performed at X-band (9250 Mc/sec) on spherical samples placed in a resonant cavity. The measurements were carried out at room temperature for yttrium garnet and at 77°K and 195°K for gadolinium garnet. Two different measuring techniques were employed, one used a pulsed magnetron (with a duty cycle of 5×10^{-5} or less), the other a frequency-swept klystron. The two methods gave equivalent results. The measurements obtained with the klystron method usually showed less scatter and, therefore, exhibited the fine structure more clearly than the measurements obtained with the magnetron method. Because of power limitations, however, the magnetron method had to be used for the larger samples that had an appreciable linewidth. For one sample the measurements were repeated using different cavities with quality factors ranging between 450 and 1200. Figure 1 shows the saturation curve obtained with the smallest sample (diameter: 0.0096 in. = 244 μ, linewidth: 4.2 oe) used in the present experiments. This sample exhibited the fine structure most clearly.

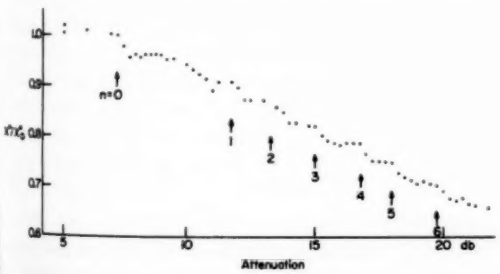

FIG. 1. Saturation curve for yttrium garnet single crystal, showing the relative susceptibility at resonance as a function of the rf field strength on a logarithmic scale. (20 db corresponds to $h^2 = 8.72\times10^{-2}$ oe^2.)

A theoretical explanation of the fine structure has been proposed by one of the authors.[1] According to this theory the fine structure arises from the discrete nature of the spin-wave spectrum. It is shown in reference 1 that a fine structure due to this effect should be observable even if the frequency separation of the spin-wave modes involved is much smaller than the inverse of their relaxation time. For the theoretical explanation it is important to realize that all spin-wave frequencies increase with increasing power level, essentially because the demagnetizing field is reduced. The potentially unstable spin waves have frequencies equal to that of the signal and their propagation vectors are at least approximately parallel to the dc magnetic field.[2] With increasing power level a series of situations is realized in which the signal frequency coincides with the effective frequency of a spin wave which propagates exactly parallel to the dc field. It is shown in reference 1 that each such coincidence gives rise to a kink in the saturation curve.

The quantitative results of the theory described in reference 1 can be stated as follows: Let $|u_0| = \chi'' h/M_S$ be the amplitude of the uniform mode (the opening angle of the precessing magnetic moment in radians), and similarly $|u_k|$ the amplitude of a spin wave with propagation vector $\vec{k}$ excited through its nonlinear coupling to the uniform mode. Here χ'' is the imaginary part of the susceptibility, M_S the saturation magnetization, and h the amplitude of the microwave magnetic field (circular component if χ'' is the circular susceptibility). If subsequent kinks in the saturation curve are labeled by an integer n (see Fig. 1), their location in a spherical sample should be determined by

$$\left\{|u_0|^2 - \tfrac{1}{6}\sum_{k\neq0}|u_k|^2\right\}_n = \text{const} + \tfrac{2}{5}(\lambda/L)n, \qquad (1)$$

where the quantity on the left should be taken at the nth kink and where λ is the wavelength of the unstable spin waves and L the diameter of the

sample. According to Suhl,[2] λ is related to the "exchange field" H_{ex} which characterizes the curvature of the spin-wave band in the vicinity of $k=0$ by

$$H_{ex}(2\pi a/\lambda)^2 = \tfrac{1}{3}(4\pi M_s), \qquad (2)$$

where a is the lattice constant. Measurements of the fine structure can, therefore, be used to infer the strength of the exchange coupling.

The first term on the left of Eq. (1) can be obtained by direct measurements; the second term must be inferred by more indirect considerations. Fortunately, the second term constitutes only a small correction in the range of moderate power levels which is primarily important in the present case. The sum of the spin-wave excitations can be obtained by using the fact that under stationary conditions the dissipated power equals the power absorbed. It is shown in reference 1 that Eq. (1) can be expressed as

$$|u_0|^2\left\{1-\tfrac{1}{8}\left(\frac{\chi_0''}{\chi''}-1\right)\right\}_n = \text{const} + \tfrac{2}{3}(\lambda/L)n, \qquad (3)$$

if it is assumed that the decay constants of the unstable spin waves equal the decay constant of the uniform mode. Here χ_0'' is the imaginary part of the susceptibility at low power levels.

In Fig. 2, we have plotted the left-hand side of Eq. (3) taken at subsequent kinks (as indicated by the arrows in Fig. 1) versus the order n, for three samples of yttrium garnet with different diameters. It is seen that the measured points fall approximately on straight lines and that the slope of these lines increases with decreasing sample diameter.

The slope s of the straight lines of Fig. 2 characterizes the separation of subsequent kinks in the saturation curve. In Fig. 3, it is plotted versus the inverse of the sample diameter. The measurements refer to yttrium garnet single crystals. The errors indicated in this figure reflect only the uncertainty in the determination of s by means of the geometrical construction shown in Fig. 2. The actual error may be larger because of the uncertainty in the calibration of the rf magnetic field. It is seen that the separation of subsequent kinks is indeed inversely proportional to the sample diameter as predicted by the theory.

The numerical value of the exchange field of yttrium garnet as obtained with the present method agrees closely with the value obtained by Edmonds

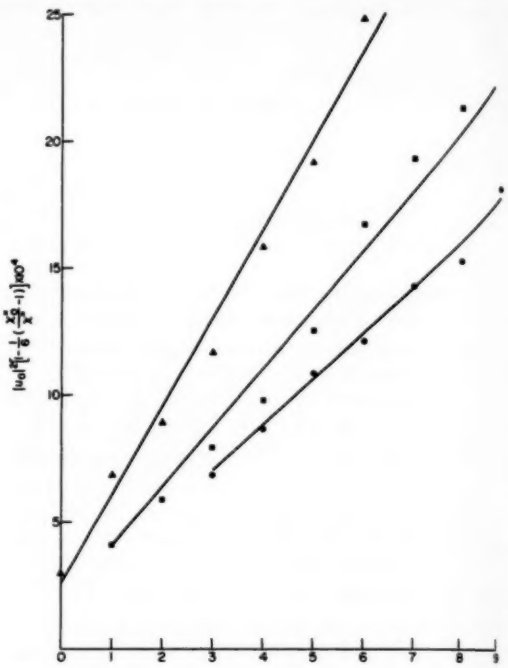

FIG. 2. Location of kinks in the saturation curves of three samples with different diameters. Since only the slope of the lines is significant, they have been shifted horizontally to avoid overlapping. Diameters: 244 μ (▲), 419 μ (■), and 645 μ (●).

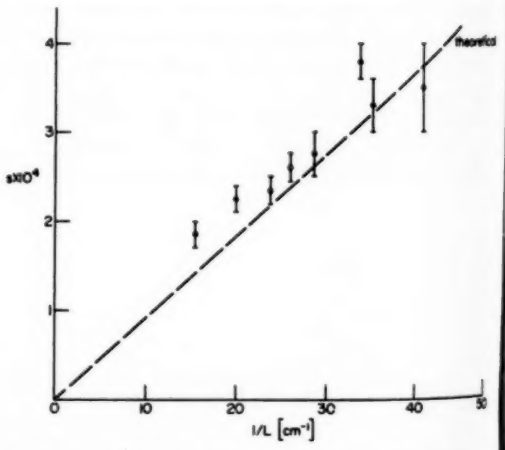

FIG. 3. Separation of subsequent kinks in the saturation curve plotted versus the inverse of the sample diameter. The line represents the theoretical prediction based on a determination of the exchange field through measurements of the specific heat at low temperatures (reference 3).

and Petersen[3] from measurements of the specific heat at low temperatures. According to reference 3 the wavelength of the unstable spin waves in spherical samples of yttrium garnet is given by $2\pi/\lambda = 4.60 \times 10^5$ cm^{-1}. The line in Fig. 3 represents the theoretical prediction for the dependence of the slope on the diameter of the sample based on this numerical value.

Stimulating discussions with Professor R. V. Jones are gratefully acknowledged.

*The portion of the work performed by J. J. Green was supported by the Air Force Cambridge Research Center.

[1]E. Schlömann, Phys. Rev. (to be published).
[2]H. Suhl, J. Phys. Chem. Solids 1, 209 (1957).
[3]D. T. Edmonds and R. G. Petersen, Phys. Rev. Letters 2, 499 (1959).

MANY-PARTICLE COOPERATIVE SCATTERING OF X-RAYS IN THE TWO-CRYSTAL SPECTROMETER

William E. Dibble
California Institute of Technology, Pasadena, California
(Received June 24, 1959)

It has been emphasized by Guinier and Fournet[1] that low-angle x-ray scattering patterns should theoretically exhibit a relatively high, extremely narrow central maximum because the entire irradiated sample will scatter coherently in the same phase at scattering angles very close to zero. This effect is very small outside of a central region where $h = (4\pi/\lambda)\sin(\phi/2)$ is less than $2\pi/d$, where d is the average dimension of the sample perpendicular to the incoming beam of x-rays.[2] The magnitude of d is almost always so large that the above effect occurs at angles too small to be observed. Parratt et al.[3] have called this and similar effects "many-atom cooperative scattering," or "ultra-small-angle" scattering. In this Letter, I shall adopt the term "many-particle cooperative scattering" and abbreviate it as "m.p.c. scattering."

This high central scattering due to the total size of the sample irradiated should be broad enough to be observed in some cases where the x-ray beam has been collimated by means of a plane, nearly perfect crystal. Such a case arises when the two-crystal spectrometer is used in parallel position for the study of low-angle x-ray diffraction patterns, with the sample placed between the two crystals.[4] M.p.c. scattering should be observable here because in this case the equivalent sample size is very small since it is determined, not by the region of the sample actually irradiated by x-rays, but by the size of the region of the sample irradiated by a coherent beam of x-rays. This means that we must consider radiation of one wavelength coming from one point on the anode of the x-ray tube. Since the collimating crystal is between the x-ray tube and the sample, the angular width of such a coherent beam of x-rays will be determined by the angular width of the reflection curve for the crystal (as, for example, the Darwin diffraction curve). The actual width of the sample irradiated by this coherent radiation will of course depend on the distance of the target of the x-ray tube from the sample. Therefore the width of the resulting m.p.c. scattering pattern will depend on both the angular width of the reflection curve of the crystal and the distance of the x-ray tube target from the sample, and will be largest for smallest values of both.

Using the half-width of the Darwin diffraction curve, and approximating this curve and also the resulting m.p.c. scattering curve by a Gaussian, the m.p.c. scattering angle at half maximum is calculated to be 1.6 seconds and 9.6 seconds, respectively, for the first and second orders of reflection of copper K_α radiation from the cleavage planes of calcite, with the sample located at 30 cm from the anode of the x-ray tube. If this distance were only 3 cm, then the above scattering angles should be multiplied by ten. The angle is much greater for the second order reflection because the Darwin pattern is much narrower in this case. The preceding estimate does not take into consideration two other causes of broadening of the pattern. The first of these broadening effects comes from the fact that the rocking curve, in the case of the two-crystal spectrometer, must be folded into the entire scattering pattern from the sample to obtain the pattern which will actually be observed,

and this of course broadens the pattern. The second effect is due to multiple scattering in the sample. We believe that both of these effects may contribute significantly to the apparent width of the m.p.c. scattering.

M.p.c. scattering appears to explain some results which have been observed in attempts to obtain low-angle x-ray scattering patterns by means of the two-crystal spectrometer in parallel position. Thus it would seem to explain the high central scattering obtained by Parratt et al.[5], particularly in the 2, -2 case, although it does not explain the scattering which they obtained at larger angles. It seems also to explain a similar central scattering obtained by Beeman and Kaesberg,[6] although the dimensions of their instrument were not given in this reference. Since the width of the m.p.c. scattering depends on the target-to-sample distance, this distance should henceforth be published in reports on work done with the two-crystal spectrometer.

The two-crystal spectrometer has also been used to define and determine x-ray absorption coefficients, as recently discussed by Parratt et al.[3] It has also been used in a similar way by Warren and others[7] to determine the total small-angle scattering of a sample. In each of the above applications the results may well prove to be dependent upon the target-to-sample distance, since this distance partially determines the width of the m.p.c. scattering discussed in this Letter, and this width in turn determines the amount of this scattering to be reflected from the second of the two crystals. Similarly, the results may prove to be more dependent on the reflection curve of the crystal than has been thought.

The author is indebted to his colleagues for valuable discussions and especially to Dr. Jesse W. M. DuMond, who also was of great assistance in preparing this Letter.

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[1]Guinier, Fournet, Walker, and Yudowitch, The Small-Angle Scattering of x-Rays (John Wiley and Sons, Inc., New York, 1955), pp. 37 and 71.

[2]A. Guinier et al., reference 1, p. 37.

[3]Parratt, Porteus, Schnopper, and Watanabe, Rev. Sci. Instr. 30, 344 (1959).

[4]Some of the references to this use of the two-crystal spectrometer, in addition to others cited in this Letter, are I. Fankuchen and M. H. Jellinek, Phys. Rev. 67, 201 (1945); J. W. M. DuMond, Phys. Rev. 72, 83 (1947); Ritland, Kaesberg, and Beeman, J. Appl. Phys. 21, 838 (1950); and L. G. Parratt, Rev. Sci. Instr. 30, 297 (1959).

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[6]W. W. Beeman and P. Kaesberg, Phys. Rev. 72, 512 (1947).

[7]B. E. Warren, J. Appl. Phys. 20, 96 (1949); H. M. Barton, Jr., and R. Brill, J. Appl. Phys. 21, 783 (1950).

STORED ENERGY OF IRRADIATED COPPER

T. H. Blewitt, R. R. Coltman, and C. E. Klabunde
Solid State Division, Oak Ridge National Laboratory,* Oak Ridge, Tennessee
(Received July 6, 1959)

It is well known that reactor irradiation substantially changes the properties of metals.[1] These changes have usually been attributed to interstitial atoms and vacant lattice sites arising from the atomic displacements which result from the collision with energetic neutrons.[2] The appearance of a large annealing peak at 30 to 50°K in the radiation-induced resistivity of samples bombarded below 20°K has led to the suggestion that interstitial atoms are mobile at this temperature and migrate to and are annihilated by vacant lattice sites. This conclusion was largely based on the fact that computations of the migration energy of interstitials indicate that they should be mobile in the 30 to 50°K range.[3] It should be noted, however, that other experiments indicate that a more complicated model than freely moving interstitials is required to explain the low-temperature annealing.[4] The fact that the formation energy of an interstitial-vacancy pair is known within narrow limits makes the measurement of the energy released important in the analysis of this peak as it gives an accurate measure of the number of defects being annihilated. In the past three years several measurements of the stored energy have been made by the authors[5-7] and it has been estimated from these measurements that the most reliable

figure was[8] 2×10^{-1} cal/mole released following a dose of 4×10^{17} neutrons/cm^2. These measurements have just been repeated under more favorable circumstances, and it is the purpose of this Letter to describe these results.

The basic technique was the same as that described previously; namely, the sample, a pill box of 60-g mass, was bombarded in good thermal contact with the cryostat so that the temperature of the sample (17°K) approached that of the cryostat (13°K). Following the bombardment of three weeks' duration in hole 12 of the Oak Ridge Graphite Reactor (1.2×10^{18} nvt), a mechanical heat[9] switch was opened and the sample isolated from the cryostat, the sample being suspended from a copper-constantan thermocouple used to detect the temperature.[10] The γ rays present in the reactor at 700-kw power level (20% of full power) were utilized as a heat source of constant intensity. The specific heat was then determined from a time-temperature curve, the specific heat being given by $C_p=(\Delta t/\Delta T)\gamma$. The homogeneous absorption of the γ heat permitted this method as the sample was always in equilibrium. An apparent decrease in specific heat can then be interpreted to be the result of the release in energy.

The results of the stored energy determination are shown in Fig. 1. Here the $\Delta t/\Delta T$ values (which were direct experimental data) are plotted as a function of the absolute temperature. A smooth curve has been drawn ignoring the points in the region from 36°K to 46°K (the dotted line in Fig. 1). The area between the smooth curve and the experimental values is representative of the energy released. The value of γ was determined by normalizing the $\Delta t/\Delta T$ values to the specific heat of copper at 35°K.[11] Unit area on Fig. 1 was found to be 0.75 cal/mole from this normalization. Since the area between the two curves was 0.756 of a unit area, the energy released between 20°K and 50°K after a bombardment of 3 weeks (1.2×10^{18} neutrons/cm^2) at 17°K was 0.57 cal/mole.

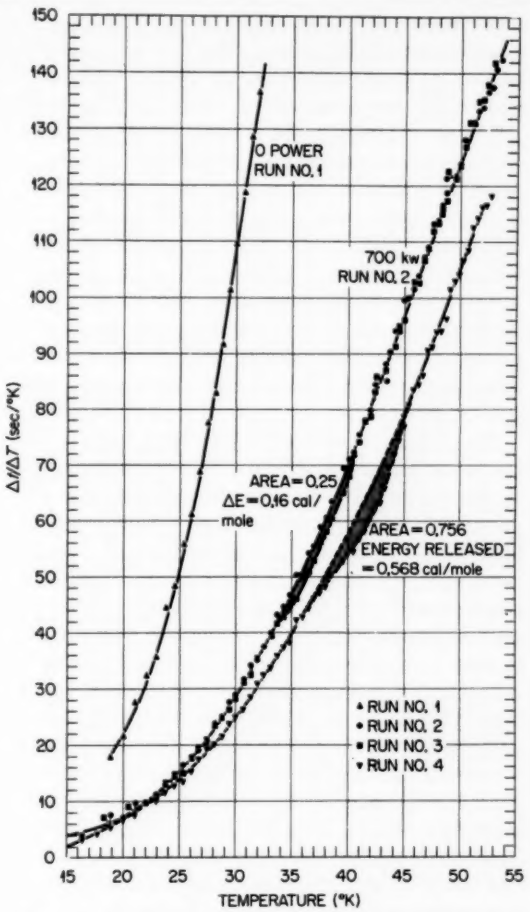

FIG. 1. Warmup curves of a copper crystal by the application of nuclear heat. The rate of warmup, $\Delta t/\Delta T$, is plotted as a function of the absolute temperature. $\Delta t/\Delta T$ values are direct experimental points and vary directly with specific heat, the ratio of proportionality being the heat input, γ. Runs 1, 2, and 3 were utilized to determine the sensitivity and reproducibility of the method, and run 4 to measure the stored energy of irradiated copper. Run 1 at zero reactor power; runs 2, 3, and 4 at nominal 700-kw power level.

Prior to the bombardment of this sample, measurements were made to determine the sensitivity of this method for measurement of the stored energy. Warmup curves of the sample were made in the pile at zero power and at a power level of 700 kw. These two runs made it possible to determine the residual reactor gamma heating rate and the nuclear heat arising from a 700-kw reactor power level. Then a third run was made at 700 kw with a simulation of energy release. Increased heat was put into the sample by raising the power over the temperature interval at which energy was expected to be released. The data of these three runs are also shown in Fig. 1. The power level was increased in the third run from 700 to 735 kw in the temperature interval from 33.8°K to 35.0°K, held constant at 735 from 35.0°K to 40.5°K, and then reduced back to 700 kw from 40.5°K to 41.3°K. After normalization of runs one and two with Giauque and Mead specific

heat values, it can be deduced that 700 kw of reactor power produces 1.08×10^{-2} cal/mole sec of gamma heat, and hence 35 kw increase in power will correspond to 5.4×10^{-4} cal/mole sec.

The area between the smooth curve of the third run and the experimental points in the region from 35.5°K to 40.1°K is 0.25 of a unit area or 0.16 cal/mole. Since the time required to raise the temperature from 35.5°K to 40.1°K was 261 sec, the excess heat applied was 0.14 cal/mole. It has thus been demonstrated that the anomalous energy, similar to that occurring when stored energy is released, can be determined to within a few hundredths of a cal/mole by utilizing the above technique.

The results of the energy release can be interpreted in accordance with a radiation damage model which attributes the 30-50°K peak to vacancy-interstitial annihilation. The number of defects annihilated, the resistivity per Frenkel pair, and the number of pairs formed per neutron displacement can be computed if the energy per pair is known. On the assumptions that diffusion occurs by vacancy migration and that interstitials migration is responsible for the 30-50°K annealing peak, it can be shown that the formation energy of an interstitial-vacancy pair must exceed 3 ev. The resistivity of an interstitial-vacancy pair and the number of such pairs formed per neutron hit has been computed in Table I assuming formation energies of 3 ev and of 5 ev, the latter value probably being the more representative.

The results of Table I do not support the simple model of interstitials migrating to and being annihilated by vacancies in the 30°K to 50°K annealing peak. It seems particularly difficult to rationalize 3 to 5 pairs formed per primary displacement with the 120 pairs suggested by theoretical treatment[12] and the measured neutron energy spectrum[5] even when localized annealing is considered. In like fashion, the resistivity of 7-12 μohm-cm per atomic percent of pairs deduced from this experiment is much higher than the theoretical value of 1.5 to 2.0 μohm-cm.[13] These conclusions thus support the earlier deductions[4] that the annealing kinetics of 30-50°K peak are difficult to interpret in terms of interstitial migration to vacant lattice sites. It thus seems that irradiation damage, in copper at any rate, arising from neutron bombardment cannot be explained in terms of simple vacancy-interstitial formation and migration

Table I. Resistivity of an interstitial-vacancy pair and the number of such pairs formed per neutron hit, for two assumed formation energies.

Assumed formation energy	3 ev	5 ev
No. of interstitial-vacancy pairs (1.2×10^{18})	1.7×10^{18}	1.0×10^{18}
No. of pairs per neutron hit ($\sigma=3\times10^{24}$ cm^2) (based on 50% recovering at 30-50°K)	5.0	2.8
Resistivity of 1% pairs	7.0×10^{-6}	12.0×10^{-6}

The authors are pleased to acknowledge the assistance of J. Diehl and J. K. Redman in the carrying out of this experiment.

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*Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

[1]Blewitt, Coltman, Holmes, and Noggle, Creep and Recovery Seminar, American Society for Metals, 1957 (unpublished), pp. 84-110.

[2]Sosin, Brinkman, and Meechan, Phys. Today 12, No. 6, 30 (1959).

[3]H. B. Huntington, Phys. Rev. 91, 1092 (1953).

[4]Blewitt, Coltman, Klabunde, Redman, and Diehl, Bull. Am. Phys. Soc. 4, 135 (1959).

[5]Coltman, Blewitt, and Noggle, Rev. Sci. Instr. 28, 375 (1957).

[6]T. H. Blewitt et al., The Techniques of Low-Temperature Physics (Butterworth Scientific Publications, London, to be published).

[7]Blewitt, Coltman, Noggle, and Holmes, Bull. Am. Phys. Soc. 1, 130 (1956).

[8]T. H. Blewitt, Symposium on Vacancies and Other Point Defects in Metals and Alloys [Inst. Metals (London), Monograph and Rept. Ser. No. 23, 213-217 (1957)].

[9]The earliest measurements established the fact that if helium gas were present, it would be absorbed on the sample. Subsequent heating would result in this gas being evolved which would destroy the isolation of the sample. Consequently, the heat switch used in this experiment is designed so that the sample is in an evacuated chamber ($\leq2\times10^{-5}$ mm Hg) at all times.

[10]The authors have established by bombardment in liquid He at 3.8°K that neutron bombardment, at least for the doses considered, does not change the output of the copper-constantan thermocouple by more than 1×10^{-7} volt (to be published).

[11]W. F. Giauque and P. F. Meads, J. Am. Chem. Soc. 63, 1897 (1941).

[12]W. S. Snyder and J. Neufeld, Phys. Rev. 94, 760 (1954).

[13]F. J. Blatt, Phys. Rev. 99, 1708 (1955).

NUCLEAR POLARIZATION VIA "HOT" CONDUCTION ELECTRONS

G. Feher
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received July 6, 1959)

Overhauser[1] has shown that under certain conditions the saturation of the electron spin resonance absorption of conduction electrons in metals produces a sizable nuclear polarization. It was subsequently pointed out by several authors[2] that this phenomenon is not limited to metals but should occur in other paramagnetic substances in which the nuclei relax via the electron spin system that has been saturated by a radio-frequency field

The purpose of the present note is to point out a polarization scheme similar in principle to the Overhauser effect but which does not require an external radio-frequency field in order to saturate the electron spin. It is based on the difference between the electron spin temperature and the temperature corresponding to the mean kinetic energy of the electrons accelerated in a dc electric field. A preliminary experiment on electrons in silicon demonstrates the existence of a large temperature difference.

We consider for simplicity a system of electrons with $S=\frac{1}{2}$ coupled to nuclei[2,3] with $I=\frac{1}{2}$ via the hyperfine interaction $A\vec{I}\cdot\vec{S}$. Let $W(+\,-\!\!-\,-\,+)$ be the probability that this interaction produces a mutual nuclear-electron spin flip (the first sign refers to m_S and the second to m_I), $N_\pm$ the number of electron spins in the $m_S=\pm\frac{1}{2}$ states, and $n_\pm$ the number of nuclei in the $m_I=\pm\frac{1}{2}$ states. Assuming that each nuclear flip can proceed only via a simultaneous electron spin flip, one obtains for the steady-state condition

$$N_+ n_- W(+\,-\!\!-\,-\,+) = N_- n_+ W(-\,+\!\!-\,+\,-). \qquad (1)$$

If the nuclei are in thermal equilibrium with the electrons, the ratio of the transition probabilities is

$$\frac{W(+\,-\!\!-\,-\,+)}{W(-\,+\!\!-\,+\,-)} = \exp[2(\mu_e-\mu_N)H/kT_R]$$

$$\simeq 1+(2\mu_e H/kT_R)-(2\mu_N H/kT_R),$$

where H is the applied magnetic field and T_R is the temperature of the reservoir that supplies the energy for the simultaneous electron nuclear flip. In the case of conduction electrons it is supplied by their kinetic energy. The electron and nuclear spin populations may be characterized by spin temperatures T_S and T_N defined by the relations

$$N_+/N_- = \exp[(2\mu_e H)/(kT_S)] \simeq 1+2\mu_e/(kT_S)$$

and

$$n_+/n_- = \exp[(2\mu_N H)/(kT_N)] \simeq 1+2\mu_N H/(kT_N).$$

From these definitions and Eq. (1) it follows that

$$n_+/n_- = 1-2\mu_e H/(kT_S)+2\mu_e H/(kT_R) + 2\mu_N H/(kT_R).$$

Therefore

$$\frac{1}{T_N}=\frac{\mu_e}{\mu_N}\left(\frac{1}{T_R}-\frac{1}{T_S}\right)+\frac{1}{T_R}. \qquad (2)$$

The above relation shows that the nuclei may be polarized along or opposite to the external magnetic field (positive or negative nuclear temperature) depending on the difference between the electron spin temperature and the temperature corresponding to their mean kinetic energy. In the regular Overhauser effect it is assumed that $T_R=T_L$, where T_L is the lattice temperature and $T_S>T_L$. The last condition is obtained by saturating the electron spin transitions. In the case of hot electrons $T_R\neq T_L$ and nuclear polarizations may be attained without the application of a saturating microwave field.

Figure 1 illustrates the nuclear polarization

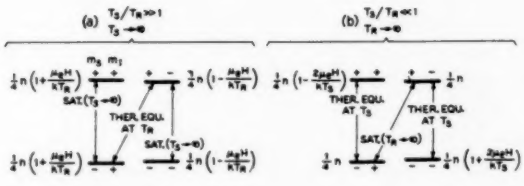

FIG. 1. Illustration of the nuclear polarization for the two limiting cases: (a) $T_S\to\infty$, nuclei are preferentially in the $m_I=+\frac{1}{2}$ state; (b) $T_R\to\infty$, nuclei are in the $m_I=-\frac{1}{2}$ state (this corresponds to a negative nuclear temperature). n in the diagram represents the total number of nuclei interacting with the electrons ($n=n_++n_-$). The quantity n_+/n_- for any value of T_R and T_S is given by Eq. (2).

for the two limiting cases: (a) $T_S \to \infty$ and (b) $T_R \to \infty$. It is seen that the magnitude and sign of the polarization correspond to the values given by Eq. (2). The energy levels in Fig. 1 correspond to an electron-nuclear system when the electron is in the vicinity of the nucleus. (For simplicity the nuclear Zeeman term has been neglected in the diagram.)

Since the above polarization scheme depends on the relative magnitudes of T_S and T_R, a preliminary experiment was performed to measure these quantities. The measurements were performed at 1.3°K on a phosphorus-doped silicon sample ($N_D = 2\times10^{16}/\text{cm}^3$, $N_A = 8\times10^{14}/\text{cm}^3$). Carriers were introduced by illuminating the sample through a germanium filter, thereby insuring that only electrons were produced.[4] A dc electric field was applied between large-area n^+ electrodes[5] and the resulting current measured. The electron spin resonance signal from the bound donor electrons was observed simultaneously at ~9000 Mc/sec. The electrical characteristic of the sample is shown in Fig. 2. At a field strength of ~150 v/cm the sample was found to break down.[6] This breakdown is believed to be the result of impact ionization of the donors by the accelerated electrons. This means that an appreciable number of electrons had acquired a kinetic energy in excess of the donor ionization energy (0.044 ev), i.e., T_R at the breakdown field will be of the order of 500°K. The deviation from Ohm's law at lower fields is an indication that the electrons are "hot," i.e., that they are not in thermal equilibrium with the lattice.[7]

The spin temperature of the free carriers T_S was obtained by measuring the spin resonance signal from the bound donors in the presence of hot electrons. There is good evidence that the spin relaxation time of the bound donor electron proceeds by a spin exchange with the free carriers,[4] which in turn relax by some other process (e.g., interactions with paramagnetic impurities). The two spin systems acquire therefore the same Boltzmann factor. The amplitude of the electron spin resonance signal from the bound donor, which is proportional to the Boltzmann factor $\mu_e H/(kT_S)$, can then be used as a convenient thermometer to measure T_S. Figure 3 shows the experimental results. The amplitude of the resonance signal at a field of 150 v/cm has decreased by a factor of two corresponding to $T_S \approx 2.6$°K which is about two orders of magnitudes lower than T_R. However, the number of electrons in these experiments (10^8 - $10^{10}/\text{cm}^3$) was too small to have produced a sizable nuclear polarization. In germanium hot electrons may be produced at lower electric fields,[7] and therefore higher current densities may be tolerated without

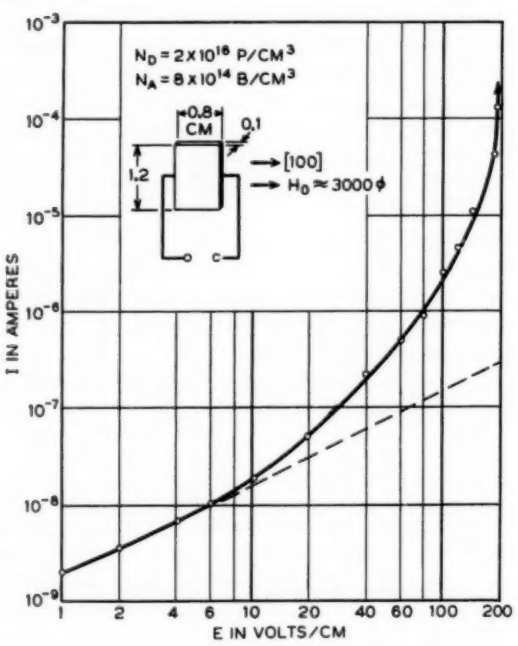

FIG. 2. Current-voltage characteristic of phosphorus-doped silicon at a lattice temperature of 1.3°K. The deviation from Ohm's law (see dashed line) indicates that the electrons are "hot." The electron spin resonance signal from the bound donors was measured simultaneously. The results are illustrated in Fig. 3.

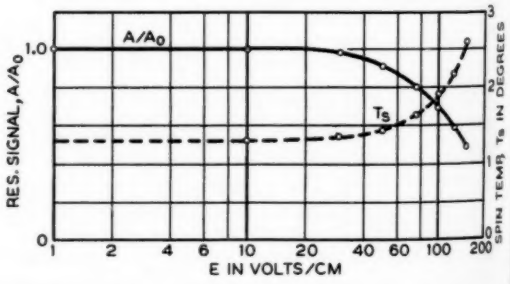

FIG. 3. Amplitude of the electron spin resonance signal from bound electrons in phosphorus-doped silicon at a lattice temperature of 1.3°K. The spins of the bound electrons are assumed to be in equilibrium with the spins of the hot electrons. The amplitude of the signal may therefore be used to measure T_S. The electrical characteristic of the same sample is illustrated in Fig. 2.

appreciably heating the lattice. Experiments on germanium are in progress.

A temperature difference between T_R and T_S may also be obtained in systems in which the free carriers relax via spin-orbit coupling.[8] In this case the spin relaxation time may be several orders of magnitude longer than the electron-lattice collision time. As a result T_S will lag behind T_R. If the electrons are accelerated in an electric field gradient, a difference between T_R and T_S will be produced. The sign of the nuclear polarization will then depend on the sign of the electric field gradient.

Another possible application of the saturation of the electron spin resonance signal in the presence of hot electrons seems worth mentioning. If the hot electrons could preferentially saturate the outer levels of a three-level system, a maser would be realized which would not require the high pumping frequency that is presently used.[9]

It is a pleasure to acknowledge many helpful discussions with P. W. Anderson and H. Suhl which provided the stimulus for the above work, and to thank E. A. Gere for his assistance in the experiments and I. M. Mackintosh for the preparation of the n^+ contacts.

[1]A. W. Overhauser, Phys. Rev. 92, 411 (1953).

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[3]This discussion, as well as the Overhauser effect, is of course not limited to electron-nuclear systems but is applicable to any two interacting spin systems (e.g., conduction electrons interacting with bound electrons).

[4]G. Feher and E. A. Gere, Phys. Rev. (to be published).

[5]The n^+ contacts were prepared by I. M. Mackintosh. 5×10^{20} P/cm^2 were diffused to a depth of ~ 0.0003 in. and a 500A gold layer evaporated on top of it.

[6]Such a breakdown in silicon was observed at 20°K by W. Kaiser and G. H. Wheatley (to be published). It is in contradiction with the conclusions of Lampert et al. [Lampert, Herman, and Steele, Phys. Rev. Letters 2, 394 (1959)].

[7]For a review article on this subject, see S. H. Koenig, J. Phys. Chem. Solids 8, 227 (1959).

[8]R. J. Elliott, Phys. Rev. 96, 266 (1954).

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CYCLOTRON RESONANCE IN ALUMINUM*

D. N. Langenberg and T. W. Moore
Department of Physics, University of California, Berkeley, California
(Received June 15, 1959)

We have observed cyclotron resonance in a single-crystal sample of aluminum at 24 kMc/sec and 4.2°K. The results indicate the presence of two distinct groups of carriers with properties consistent with the theoretical analysis of Heine.[1]

Changes in power absorption in the sample were observed using a standard microwave reflection spectrometer. Both absorption and absorption-derivative measurements were made, the latter using magnetic field modulation.

The sample was cut from a single crystal of zone-refined aluminum using a string saw wetted with $CuCl_2$ solution. The resulting plane surface was then smoothed and electropolished. This surface was a {110} plane and formed part of the end wall of a TE_{011} cylindrical cavity which was mounted with the magnetic field parallel to the sample surface. The cavity together with the sample could be rotated about their common axis.

Figure 1 shows experimental curves of absorption and absorption-derivative versus magnetic field taken with the magnetic field 10° from a ⟨110⟩ crystal axis. At fields above 2 kilo-oersteds the absorption curve shows a component periodic in $1/H$ superimposed on a monotonically decreasing component, a behavior similar to that previously reported in copper.[2] The variation is (not surprisingly) somewhat different from that predicted by Azbel' and Kaner[3] for a free-electron gas. The absorption-derivative curve shows the oscillations more clearly. These oscillations correspond to a cyclotron mass of $1.5m_0$ and an $\omega\tau$ of about 10.

For some sample orientations the hump which appears at 2 kilo-oersteds on the absorption curve in Fig. 1 is resolved into distinct peaks. Experimental curves for such an orientation are shown in Fig. 2. These curves were taken with the magnetic field parallel to a ⟨111⟩ crystal axis. The peaks correspond to a cyclotron mass

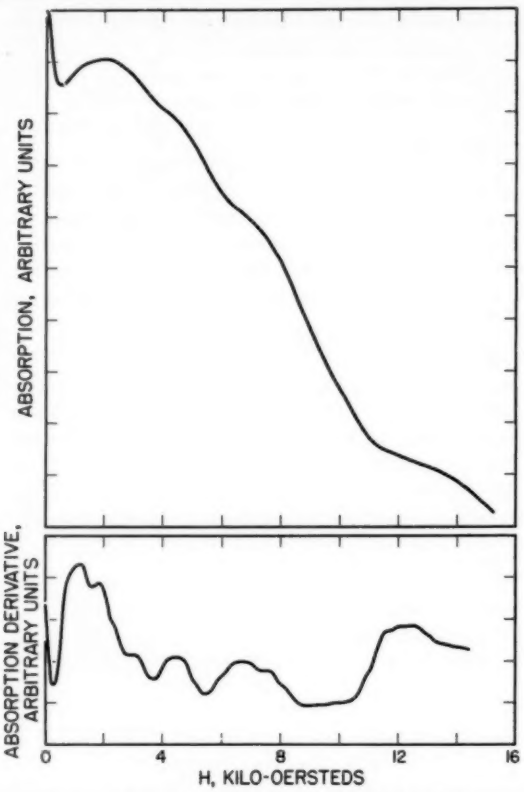

FIG. 1. Absorption and absorption-derivative curves for aluminum with magnetic field 10° from a ⟨110⟩ axis in a {110} plane. $\vec{J}_{rf}$ in {110} plane and 65° from $\vec{H}$. $f = 23.54$ kMc/sec.

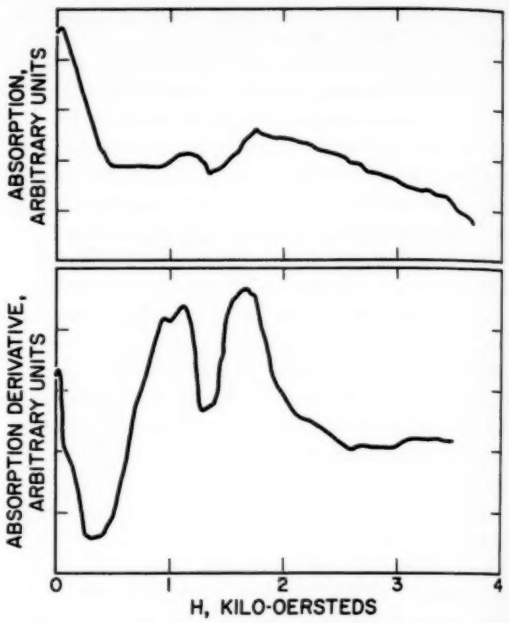

FIG. 2. Absorption and absorption-derivative curves for aluminum with magnetic field parallel to a ⟨111⟩ axis. $\vec{J}_{rf}$ in {110} plane and 90° from $\vec{H}$. $f = 23.54$ kMc/sec.

of $0.18m_0$. For this orientation the oscillations corresponding to the higher mass were not well resolved.

The dependence of the resonances on sample orientation with respect to the magnetic field has been explored. The present data do not permit a detailed analysis, but some general statements can be made. Some trace of the high-mass resonance appears for most orientations of the sample. This resonance is most clearly resolved in a region perhaps forty-five degrees wide centered on a ⟨110⟩ direction. Over the range of orientations for which some estimate of cyclotron mass could be made, the mass was quite isotropic; the variation was of the order of 10% or less. The anisotropy in the low masses was of the order of 50%.

We believe that the low masses are associated with the holes ($\sim 4\times10^{-3}$ hole/atom) located, according to Heine, at the corners of the first Brillouin zone and observed by Gunnersen[4] using the de Haas–van Alphen effect, and that the high-mass resonances are associated with the major part of the Fermi surface which is located in the second zone. No de Haas–van Alphen effect attributable to this part of the surface has been observed. The electron pockets ($\sim 10^{-5}$ electron/atom) observed by Gunnersen and located at the corners of the third zone by Heine probably do not contribute to the resonances observed in the present work and it is doubtful that they can be detected with the present cyclotron resonance methods.

We should like to express our appreciation to G. Meyrick of the University of Bristol for his kindness in providing the aluminum single crystal used in this work.

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* Supported by the Air Force Office of Scientific Research and the Office of Naval Research.

[1]V. Heine, Proc. Roy. Soc. (London) A240, 340, 354, 361 (1957).

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CYCLOTRON RESONANCE IN ALUMINUM*

E. Fawcett
Royal Radar Establishment, Great Malvern, England
(Received June 22, 1959)

Cyclotron resonance has been observed in aluminum at 36 kMc/sec and 4.2°K, with effective masses in the range from about $0.1m_0$ to $0.4m_0$.

The surface resistance is measured by a calorimetric method with an experimental arrangement similar to one described previously by the author.[1] The microwave current direction in the plane surface of the fixed sample is vertical; the magnetic field can be rotated in a horizontal plane but is normally set parallel to the sample plane. The samples are of zone-refined aluminum of nominal purity approaching 99.9999% supplied by the A.I.A.G. Research Laboratories, Switzerland. After rolling and punching out disks of convenient size, recrystallization occurs at room temperature,[2] and the grain size is large enough to cover the end of the cavity with a single crystal. After annealing at about 600°C for 3 hours to complete the recrystallization and further relieve mechanical strains, the sample is electropolished.

Figures 1 and 2 show the variation of the surface resistance with magnetic field up to 4.5 kilo-oersteds. For each orientation there is evidence for cyclotron resonance of two distinct effective masses. The resonances most clearly resolved, in some cases with subharmonics up to the fifth, are indicated by arrows. These show the positions of the minima of the resistance according to the theoretical formulation of cyclotron resonance for a free electron metal given by Mattis and Dresselhaus[3]; their Eq. (27) for the surface impedance (see also Rodriguez[4]) differs slightly from the corresponding Eq. (2.4) obtained by Azbel' and Kaner[5] using a different approximation procedure.

Figure 3 shows the effect of tilting the magnetic field out of the sample plane. The minimum at about 3 kilo-oersteds broadens when the inclination ψ equals $\pm 2°$ and disappears completely at $\psi = \pm 4°$, while the minimum at about 1.5 kilo-oersteds is still well resolved at $\psi = \pm 4°$. This behavior corroborates the interpretation of the minima as being due to different groups of carriers, the one having about twice the effective mass of the other. According to the alternative interpretation that the two minima correspond to the fundamental and second subharmonic of the same group of carriers, the minimum at the lower field due to carriers describing cyclotron orbits at half the microwave frequency would evidently disappear first.

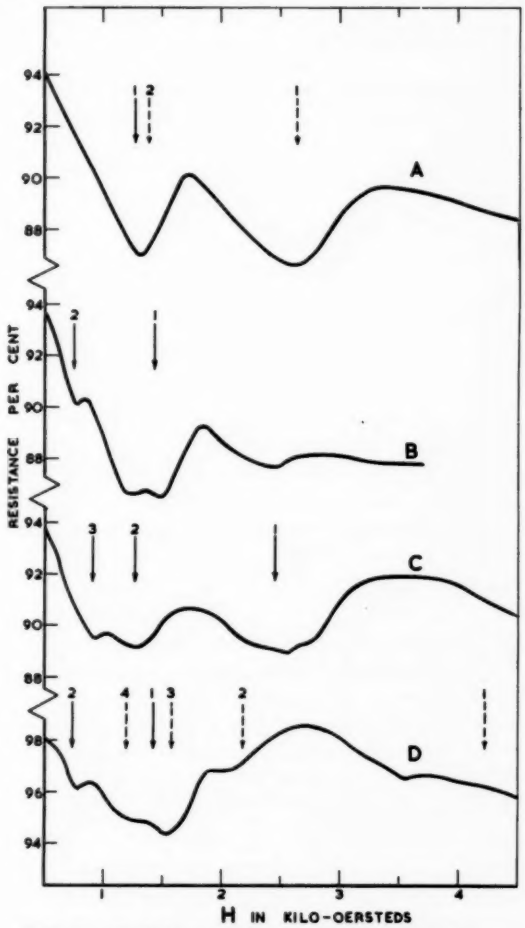

FIG. 1. Cyclotron resonance in aluminum at 36 kMc/sec and 4.2°K in magnetic fields up to 1 kilo-oersted. The ⟨110⟩ axis lies in the sample plane and the normal makes an angle θ with ⟨001⟩. The magnetic field is in the sample plane at 90° to the current direction. Arrows show positions and order of subharmonics calculated for a free electron metal with $\omega\tau = 10$ and effective mass ratios as follows:

A, $\theta = 7°$, $H \parallel \langle 110 \rangle$, $\downarrow 0.11$, $\downarrow 0.23_5$.
B, $\theta = 7°$, $H \perp \langle 110 \rangle$, $\downarrow 0.12_5$.
C, $\theta = 18°$, $H \parallel \langle 110 \rangle$, $\downarrow 0.21_5$.
D, $\theta = 18°$, $H \perp \langle 110 \rangle$, $\downarrow 0.12_5$, $\downarrow 0.37$.

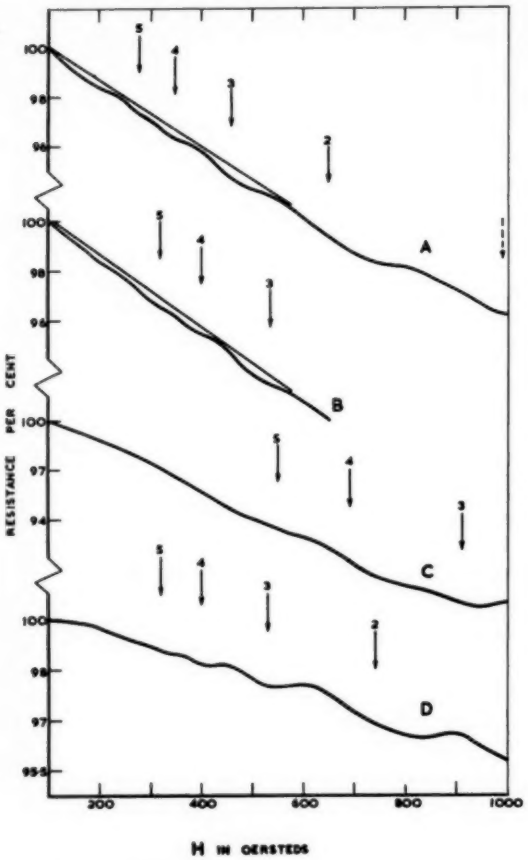

FIG. 2. Cyclotron resonance in aluminum at 36 kMc/sec and 4.2°K in magnetic fields between 0.5 and 4.5 kilo-oersteds. The orientations and effective mass ratios are as for Fig. 1.

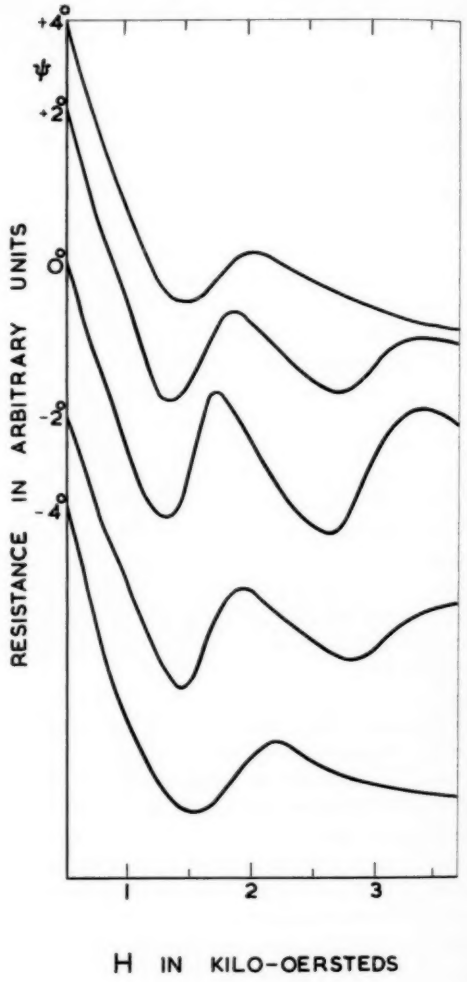

FIG. 3. Cyclotron resonance in aluminum at 36 kMc/sec and 4.2°K for the orientation A of Figs. 1 and 2, as the magnetic field is tilted to make an angle ψ with the sample plane.

An approximate estimate of the relative amplitudes of successive subharmonics shows them to be roughly in agreement with the theoretical values for a free-electron gas with $\omega\tau \sim 10$ (Mattis and Dresselhaus[3]). The fundamentals have amplitudes between one and two percent of the resistance in zero field. This value is somewhat higher than, but in order of magnitude agreement with, the expected contribution from the 3.6×10^{-3} hole per atom deduced by Gunnersen[6] from his measurements of the de Haas–van Alphen effect in aluminum (see also Heine[7]). The effective mass $0.125m_0$ agrees reasonably well with Gunnersen's value $0.15m_0$ for the same orientation.

The effective masses of the low-mass carriers agree qualitatively with the values found by Langenberg and Moore.[8] Resonances corresponding to their high-mass carriers were not observed in fields up to about 6 kilo-oersteds, probably because of too low an amplitude of the lower subharmonics. The effective mass $0.11m_0$ for orientation A agrees well with the value $0.11m_0$ for the same orientation calculated by Heine from

the shape of the hole pockets (but compare $0.15m_0$ observed experimentally by Gunnersen from the temperature variation of the de Haas–van Alphen oscillations).

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DETECTION OF COHERENT BREMSSTRAHLUNG FROM CRYSTALS*

O. R. Frisch† and D. N. Olson
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
(Received July 2, 1959)

When fast electrons (of several hundred Mev or more) pass through a crystal we expect the bremsstrahlung to be enhanced[1] and linearly polarized[2] if the electrons travel in a direction nearly parallel to some densely occupied rows of atoms. In simple terms, the reason is that an electron of energy $E_1=\gamma_1 mc^2$ ($\gamma_1 \gg 1$) has a speed of $v=c[1-1/(2\gamma_1^2)]$ and can travel a distance $A=2\gamma_1^2\lambda\!\!\!^{-}$ before falling back by $\lambda\!\!\!^{-}$ behind a quantum (of wavelength $\lambda=2\pi\lambda\!\!\!^{-}$) which it is racing. This "coherence length" A can be several times the distance a between atoms in a row, and if an electron travels parallel to such a row one would expect A/a nuclei to cooperate coherently in the emission of a bremsstrahlung quantum; compared to a crystal not so aligned, the radiation should be stronger by a factor A/a. This factor is reduced[1] by thermal vibrations and by multiple scattering but may be still well above unity.

In estimating A, we have ignored the fact that after emitting the quantum the electron has less energy $E_2=\gamma_2 mc^2=E_1-\hbar c/\lambda\!\!\!^{-}$. The semiclassical argument above cannot allow for this; but the uncertainty principle gives the right answer. If both the electron and the emitted quantum go in the forward direction then the momentum that has to be taken up by the lattice is calculated as $P_L=(mc/2)(\gamma_2^{-1}-\gamma_1^{-1})$. The place where such a small momentum has been deposited cannot be located better than within $\hbar/P_L=2\gamma_1\gamma_2\lambda\!\!\!^{-}$; this must be the correct expression for A and indeed agrees with the previous expression if γ_1 and γ_2 are taken as equal.

Alignment has to be accurate to about $r_B/Z^{1/3}A$ or the enhancement will be reduced (r_B = Bohr radius = 5.3×10^{-9} cm). Deliberate misalignment of that order will produce fairly strong linear polarization of the quanta,[2] and such radiation may be of value for the study of photonuclear reactions; indeed this should give greater intensity than one gets in the fringe[3] of a beam from an ordinary target.

We have found, experimentally, about the expected enhancement, using a small crystal of germanium. It was mounted in the Cornell synchrotron in such a way that the 1-Bev electrons, spiralling in when the rf accelerating voltage was turned off, would cut across one of its edges, approximately in the [110] direction (face diagonal) on which there is a nucleus every 4.0 A. This produced the usual narrow beam of bremsstrahlung; the central portion (one milliradian around the axis) was selected by a lead collimator and cleared of charged particles by a magnetic field (in vacuo). It then passed successively through two plastic scintillation counters S and H, separated by 5 cm of lead and preceded by 3 mm of lead. Because of showers developing in the lead, the second counter H would be more sensitive to hard quanta whereas S would respond about equally to all quanta above 50 Mev. An increase in the ratio S/H should indicate, despite fluctuations in beam intensity, the expected enhancement of the softer x-rays as the crystal approached the correct alignment.

The crystal was aligned within about 2° on the basis of its Laue pattern; it could then be turned in small steps about a horizontal and a vertical

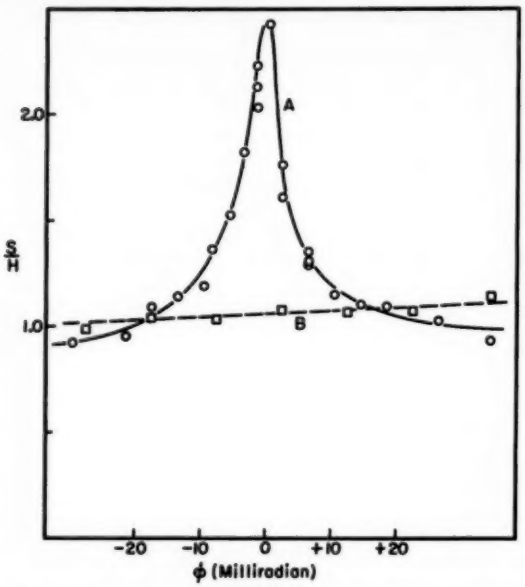

FIG. 1. The relative change measured in the ratio of soft quanta to hard quanta (S/H) as the crystal was turned through ϕ with $\psi \simeq 0$ (curve A) and $\psi \simeq 20$ milliradians (curve B).

axis (both normal to the electron beam) by angles ϕ and ψ, respectively. Usually a change in either ϕ or ψ caused only a small gradual change (Fig. 1, curve B) in S/H, due perhaps to the changed aspect of the crystal as seen by the beam. But for one particular combination of ϕ and ψ S/H is about doubled (curve A). The half-width of the effect is about 0.3°, both for ϕ and ψ. If we assume that the change in S/H is chiefly caused by the enhancement of radiation around 100 Mev, we find $A = 4 \times 10^{-7}$ cm and $\Delta\phi = 4$ mrad in reasonable agreement with the observed width.

There seems little doubt that the enhancement we find is the Überall effect even though it is much smaller than $A/a \simeq 10$. It would have been desirable to verify the polarization, but our work had to be stopped at this point. We can offer no explanation for the negative result of Panofsky and Saxena[4]; compared to their arrangement, the strong collimation we used and the fact that our counter S was sensitive down to low x-ray energies would both tend to increase the coherence effect.

We wish to thank E. Belmont of the Red Bank, New Jersey, Division of Bendix Aviation Corporation for supplying us with germanium crystals and Dr. R. R. Addiss and Mr. R. L. Schwoebel for orienting them by taking Laue photographs. One of us (O.R.F.) is most grateful to Professor R. R. Wilson for the hospitality extended to him at the Newman Laboratory of Nuclear Studies during his sabbatic leave from the University of Cambridge, Cambridge, England.

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†Permanent address: Cavendish Laboratory, Cambridge, England.

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DE-EXCITATION OF μ-MESONIC ATOMS

N. A. Krall and E. Gerjuoy
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation, San Diego, California
(Received June 30, 1959)

Experiments by Stearns and Stearns[1] have shown that during the de-excitation of a μ-mesonic atom, as the μ seeks its ground state, some nonradiative process competes much more favorably with radiative transitions than does the usual Auger process.[2] It has been suggested[3] that collisions with neighboring atoms could cause the μ meson to fall from the $2p$ to the $1s$ level, with the released energy used to eject an electron from the colliding atom. The size of this effect was found to be too small to explain Stearns' data.[4]

The subject of this Letter is the possibility of collisional de-excitation of the radiating $2p$ mesonic atom level to the metastable $2s$ level, whose radiative lifetime is long enough to permit Auger

Table I. Splitting of the $2p_{1/2}$ and $2s_{1/2}$ levels in μ-mesonic atoms, arising from vacuum polarization and finite nuclear size. For low Z the $2s$ level lies below the $2p$ level in energy.

Atom:	H^1	He^4	Li^7	Be^9	B^{11}	C^{12}	O^{16}
$(E_{2p_{1/2}} - E_{2s_{1/2}})$ in ev	0.21	1.5	3.0	4.6	1.5	-7	-60

or other nonradiative decay from the $n=2$ to the ground $n=1$ state. Table I summarizes the μ-mesonic $2s-2p$ splittings in the elements $Z \leq 8$, based on the calculations of Foldy and Eriksen,[5] but corrected for newer values of nuclear radii.[6] The cross-over of the $2p$ and $2s$ levels at $Z \cong 5$ results from the different Z dependence of the vacuum polarization and nuclear size effects. Thus, since the $2p-2s$ splittings typically are larger than thermal energies, for $Z>5$ collisions are almost always energetically incapable of raising the $2p$ level to the $2s$; for $Z \leq 5$, on the other hand, collisions can de-excite the $2p$ to the $2s$, but a mesonic atom in the $2s$ state only very infrequently is raised back to the $2p$. It is provocative that the deficiency in K-series x-rays is observed in precisely those elements $Z \leq 5$ in which the $2s$ level lies below the $2p$ (compare Table I with Fig. 7 of Stearns and Stearns[1]).

Because the $2p-2s$ energy change ΔE is so much smaller, and because the proton and μ-meson masses are more nearly matched then the μ-meson and electron masses, collisional $2p-2s$ de-excitation with the colliding atom carrying off kinetic energy ΔE is much more probable than the $2p-1s$ mechanism previously considered,[3] wherein the electron had to carry off the much larger energy release. For instance in hydrogen, for a collision between a μ-mesonic atom and a proton, the $2p-2s$ de-excitation cross section in Born approximation is

$$\sigma_{\text{Born}} = \frac{18\pi^3 e^4}{\hbar^2 v_0^2}\left(\frac{M}{\Delta E}\right)^{1/2} a_\mu^{\,2},$$

which, with $\Delta E = 0.2$ ev, $a_\mu = a_0/200$, and incident velocity[3] $v_0 \cong 10^8$ cm/sec, is about $500\pi a_0^{\,2}$, many orders of magnitude larger than the Born estimate[4] for $2p-1s$ de-excitation.

To explain the Stearns' K-series data, the de-excitation cross section would not have to be larger than about $10\pi a_0^{\,2}$. Unfortunately Born approximation is unreliable and gives a large overestimate at these low energies, especially when ΔE is so small. A better estimate is $\sigma \cong \frac{1}{2}\pi b^2$, where b is the largest impact parameter for which the collision is nonadiabatic, i.e., for which $\omega^{-1}[dM(t)/dt] > \Delta E = \hbar\omega$ where

$$M(t) = \langle \psi_{2s}(\vec{r}_\mu) \left| \frac{e^2}{|\vec{r}_\mu - \vec{R}|} \right| \psi_{2p}(\vec{r}_\mu) \rangle$$

and $R(t)$ is the position of the colliding proton. For μ-hydrogen, which can easily penetrate neighboring atoms because its total charge is zero, this criterion leads to the result

$$\sigma = \tfrac{1}{2}\pi\left[\frac{3e^2 a_\mu \hbar v_0}{(\Delta E)^2}\right]^{2/3},$$

which is about $\pi a_0^{\,2}$. In mesonic atoms of higher Z the $2p-2s$ collision de-excitation cross section will be even smaller since the now non-neutral mesonic atom no longer can penetrate neighboring atoms.

The foregoing observations justify the following conclusions: (*i*) In light elements, $Z \leq 5$, $2p-2s$ collisional de-excitation probably is not rapid enough to explain Stearns and Stearns[1] K-series data, but is not negligible compared to radiative or (usual estimates of) Auger transition rates, and assuredly is much more rapid than any collisional de-excitation process between levels of different principal quantum number. (*ii*) Collisional excitation and de-excitation between levels of the same principal quantum number n is even more probable in higher shells $n \geq 3$, where ΔE is much smaller. There are no metastable levels in these shells, but the collisions will tend to statistically distribute the μ meson among levels of the same n, thereby modifying previous estimates[2] of the transition rates from $n \geq 3$ and of the percentages of μ-mesonic atoms ultimately reaching the $2p$ and $2s$ states. (*iii*) The effect (*ii*), and the effect (*i*) if large enough, will depend on the immediate environment of the μ-mesonic atoms. Thus in the light elements, where the radiative rates do not dominate collisional and Auger de-excitation rates, the radiative yields using chemical compounds should differ from the yields in pure elements, due account being taken of the possibility of meson charge transfer.

We are happy to acknowledge discussions with Dr. Martin Stearns, Dr. Michel Baranger, and Dr. Jeremy Bernstein.

[1] M. Stearns and M. B. Stearns, Phys. Rev. 105, 1573 (1957).

[2]G. R. Burbridge and A. H. de Borde, Phys. Rev. 89, 189 (1953); A. H. de Borde, Proc. Phys. Soc. (London) A67, 57 (1954).
[3]T. B. Day and P. Morrison, Phys. Rev. 107, 912 (1957).
[4]J. Bernstein and Ta You Wu, Phys. Rev. Letters 2, 404 (1959).
[5]L. Foldy and E. Eriksen, Phys. Rev. 95, 1048 (1954).
[6]R. Hofstadter, Annual Review of Nuclear Science (Annual Reviews, Inc., Palo Alto, 1957), p. 231.

ERRATA

THEORY OF SOLID He³. Newton Bernardes and Henry Primakoff [Phys. Rev. Letters 2, 290 (1958)].

This Letter presented a theory of the properties of solid He³ on the basis of a Heitler-London model of a solid. Our calculations indicated that (1) solid He³ should behave as a nuclear antiferromagnet with a paramagnetic Curie temperature $T_C \cong 0.3°K$ at $p \cong 30$ atmos, and (2) the melting curve of He³ should have a minimum near 0.35°K and a maximum below 0.1°K.

Our calculations have been revised and a numerical mistake was discovered. As a consequence we now find a value $T_C \cong 0.1°K$ for the Curie temperature at $p \cong 30$ atmos which is in better agreement with the experimental results of Fairbank and Walters.[1] In order to obtain a revised melting curve in a self-consistent way we recalculated the entropy of the solid using the value $T_C = 0.1°K$. The change in volume, $V_{liq} - V_{sol}$, was again taken equal to 1 cm³/mole and independent of temperature. The entropy of the liquid was obtained by extrapolating the experimental values of Brewer and Daunt[2] to appropriate pressures. In a first approximation we used values of the entropy of the liquid extrapolated to 30 atmos, and a melting curve was obtained in first approximation by using the equation of Clapeyron, and taking $p = 29.3$ atmos as the melting pressure at $T = 0.37°K$ (the temperature where our theoretical curve for the entropy of the solid crosses the extrapolated experimental curve[2] for the entropy of the liquid). A second approximation for the melting curve was obtained by using, in the Clapeyron equation, extrapolated values of the entropy of the liquid corresponding to the melting pressure as given by our results in first approximation; on the other hand, we neglected the variation of the entropy of the solid with varying melting pressure. The resulting melting curve was found to lie lower than the one obtained in first approximation, and much lower than the melting curve obtained on basis of the assumption made by Pomeranchuk,[3] i.e., that spin alignment in the solid only occurs below 10^{-7} °K.

Our results for the melting curve are shown in Fig. 1 together with smoothed experimental values of Baum, Brewer, Daunt, and Edwards[4] who, avoiding the usual blocked capillary method, succeeded for the first time in observing the melting curve of He³ below the temperature of the minimum.

Experiments at lower temperatures would be of great interest since a further distinction be-

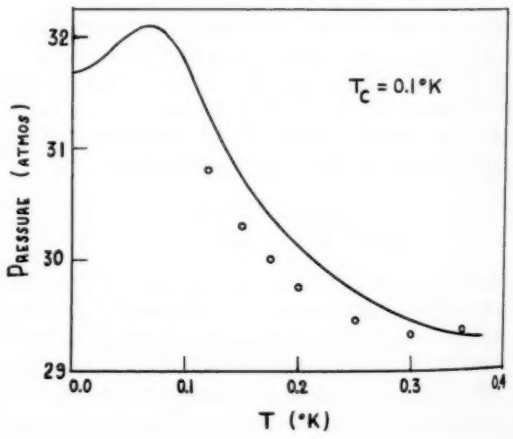

FIG. 1. Melting curve of He³: solid line calculated as described in the text; the circles correspond to experimental points.[4]

tween our theory and Pomeranchuk's[3] may be obtained by the observation or otherwise of the maximum in the melting curve at $T \cong 0.075°K$.

[1]W. M. Fairbank and G. K. Walters, Suppl. Nuovo cimento 9, 297 (1958).

[2]D. F. Brewer and J. G. Daunt, Phys. Rev. (to be published).

[3]I. Pomeranchuk, J. Exptl. Theoret. Phys. U.S.S.R. 20, 919 (1950).

[4]Baum, Brewer, Daunt, and Edwards, this issue [Phys. Rev. Letters 3, 127 (1959)]; we are indebted to these authors for making their results available to us before publication.

MESON-THEORETICAL ORIGIN OF THE SPIN-ORBIT COUPLING BETWEEN TWO NUCLEONS

N. Tzoar, R. Raphael, and A. Klein
[Phys. Rev. Letters 2, 433 (1959)]

Equation (2) is incorrect. The correct result is

$$V_{LS} = -\mu\left(\frac{\mu}{M}\right)\left(\frac{f^2}{4\pi}\right)^2\left\{(3+2\vec{\tau}_1\cdot\vec{\tau}_2)(2+4x+4x^2+2x^3)\left(\frac{e^{-2x}}{x^6}\right) - (3-2\vec{\tau}_1\cdot\vec{\tau}_2)\left(\frac{2}{\pi}\right)\left(\frac{1}{x^4}\right)\left[xK_0(x)+2K_1(x)\right]^2\right.$$

$$+\zeta_2(\vec{\tau}_1\cdot\vec{\tau}_2)8(1+x)^2\left(\frac{e^{-2x}}{x^6}\right)+\left(\frac{\mu}{M}\right)\left[2\zeta_2\zeta_4(\vec{\tau}_1\cdot\vec{\tau}_2)-3\zeta_3\right]\left(\frac{2}{\pi}\right)\left[K_1(2x)\left(\frac{5}{2x^6}+\frac{1}{x^4}\right)+K_0(2x)\frac{5}{2x^5}\right]$$

$$\left.+\left(\frac{\mu}{M}\right)\zeta_4(\vec{\tau}_1\cdot\vec{\tau}_2)\left(\frac{8}{\pi}\right)\left[K_1(2x)\left(\frac{25}{2x^6}+\frac{8}{x^4}\right)+K_0(2x)\left(\frac{25}{2x^5}+\frac{2}{x^3}\right)\right]\right\}.$$

This does not modify qualitatively the results shown in Fig. 1, but the spin-orbit potential in triplet even states is now more strongly repulsive. We are indebted to Professor M. Sugawara for convincing us of the existence of calculational errors.

TABLE OF CONTENTS FOR VOLUME 2, No. 12; and AUTHOR INDEX TO VOLUME 2 [Phys. Rev. Letters 2, 525 (1959)].

The following entry was inadvertently omitted from the Table of Contents for Volume 2, No. 12:

Stimulated Emission of Radiation by Relativistic Electrons in a Magnetic Field . . . . . Jurgen Schneider 504

The page number of this Letter was also omitted from the Author Index to Volume 2, and should be inserted (third item in the right-hand column of p. 532).

PROTONS IN THE EARTH'S MAGNETIC FIELD. Stanley C. Freden and R. Stephen White [Phys. Rev. Letters 3, 9 (1959)].

On page 10, first column, fourth last line, "distribution proportional to $T^{-1.3}$..." should read "distribution (in protons/cm² sec) proportional to $T^{-1.0}$...".

VAN ALLEN BELT PROTONS FROM COSMIC-RAY NEUTRON LEAKAGE. Wilmot N. Hess [Phys. Rev. Letters 3, 11 (1959)].

In the equation for dE/dx in the third paragraph (page 11, column 2, fifth last line) there was an unfortunate error of a factor of 10. The equation should read

$$dE/dx = 0.116E^{-0.586}\ \text{Mev/cm of NTP air.}$$

As a result, the expression for the proton lifetime (page 12, middle of column 2) becomes

$$\tau = 2.1\times10^{-9}MT^{1.24}\ \text{sec},$$

which gives $\tau = 6\times10^9$ sec for the 100-Mev proton considered in the second last paragraph. This makes the proton flux (page 12, column 2, fifth last line) $F = 1\times10^5$ protons/cm² sec. These changes do not affect the conclusions of the article. The equilibrium proton spectrum, $N(E)$, given in the article is a particle density, not a flux.

ABSTRACTS

In this section are printed the abstracts of Articles that have been forwarded to The American Institute of Physics for publication in THE PHYSICAL REVIEW. In quoting information obtained from this section before the appearance of the corresponding Article, reference should be made to "Physical Review (to be published)" rather than to this Journal.

REMARK ON RECURRENCE TIMES. M. Kac, Department of Mathematics, Cornell University, Ithaca, New York (Received February 13, 1959).

A simple derivation is given of the mean recurrence time of a linear chain of harmonically bound particles. The derivation is based on a formula of Smoluchowski.

THIRD LAW OF THERMODYNAMICS. Gottfried Falk,* Department of Physics, New York University, University Heights, New York (Received November 19, 1958).

A new formulation of the third law is proposed stating a universal connection between the lower limits of the energy and the entropy of any physical system. As consequences of the new theorem are derived the Nernst heat theorem, a theorem concerning the lowest energy state of mixtures, and the nondegeneracy of the energetic ground state of physical systems.

*On leave of absence from the Institute of Theoretical Physics, Technische Hochschule, Aachen, Germany. Now at the Institut für Kernverfahrenstechnik, Technische Hochschule, Karlsruhe, Germany.

CONDITIONS FOR EQUILIBRIUM AT NEGATIVE ABSOLUTE TEMPERATURES. Bernard D. Coleman, Mellon Institute, Pittsburgh, Pennsylvania, and Walter Noll, Department of Mathematics, Carnegie Institute of Technology, Pittsburgh, Pennsylvania (Received February 20, 1959).

In the classical phenomenological thermodynamic theory of Gibbs, equilibrium is defined as the state of maximum entropy at constant energy, and a theorem is proved (the energy theorem) which asserts that the equilibrium state is the state of minimum energy at fixed entropy. This theorem is not true for systems at negative absolute temperatures. By examining a familiar statistical model which can exhibit negative absolute temperatures, we find the correct form of the energy theorem. It turns out that at negative absolute temperatures the state of equilibrium of a system with a given entropy is that in which the system has its highest energy.

SELF DIFFUSION AND NUCLEAR RELAXATION IN He^3. R. L. Garwin and H. A. Reich, IBM Watson Laboratory at Columbia University, New York, New York (Received March 3, 1959).

Direct spin-echo measurements of diffusion coefficient (D) and spin relaxation time (T_1 and T_2) have been performed on He^3, with an accuracy ~2% in the range 0.5°K to 4.2°K and at pressures to 67 atmos in the liquid, in the solid, and in dilute solutions of He^3 in He^4. Unactivated diffusion is observed to the lowest temperatures in the liquid, but not in the solid. By measurement of D at 19 atmos we find an activation energy of 13.7°K for the production of scatterers in He II. There is an extended discussion of experimental details.

TEMPERATURE-DEPENDENT DEFECT PRODUCTION IN BOMBARDMENT OF SEMICONDUCTORS. G. K. Wertheim, Bell Telephone Laboratories, Murray Hill, New Jersey (Received March 9, 1959).

A model is proposed to explain the observed dependence of the defect production rate on temperature when semiconductors are bombarded with electrons of sufficient energy to produce vacancy-interstitial pairs. The decreased defect density observed after low-temperature bombardment may be due to the production of a metastable vacancy-interstitial pair which may either anneal or form the defect usually observed. A temperature dependence in the production rate arises if these two competing processes have different activation energies.

COLLECTIVE EXCITATIONS IN THE THEORY OF SUPERCONDUCTIVITY. G. Rickayzen, Department of Physics, University of Illinois, Urbana, Illinois (Received March 5, 1959).

The complex dielectric constant of a superconductor and the Meissner effect are derived in a manner which is gauge invariant, from the theory

of superconductivity due to Bardeen, Cooper, and Schrieffer. The collective excitations are important in maintaining gauge invariance; the longitudinal collective excitations ensure that a static vector potential produces no longitudinal current and the transverse collective excitations contribute to the Meissner current an amount which depends on the angular properties of the two-body interaction. This contribution is estimated to be small. An earlier calculation of ultrasonic absorption in superconductors is justified. The whole investigation is based upon the generalized random phase approximation introduced by Anderson and applies whether or not the Coulomb interaction between the electrons is taken into account. The equations of motion are linearized in such a way that the exchange terms are automatically screened if the Coulomb interaction is, in fact, taken into account. The region of applicability of most of the results is limited by the approximations to temperatures at or near the absolute zero.

HIGH-TEMPERATURE THERMAL CONDUCTIVITY OF INSULATING CRYSTALS: RELATIONSHIP TO THE MELTING POINT. Robert W. Keyes, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (Received March 5, 1959).

The Lindemann melting rule is used to eliminate the elastic constant from the thermal conductivity formula proposed by Lawson. The thermal conductivity is thus obtained as a function of density, atomic weight, and melting temperature. The introduction of a dependence on bond character allows a major fraction of the available high-temperature thermal conductivity data to be reproduced within a factor of two. A dependence of thermal conductivity on mass ratio of the type found theoretically by Blackman for diatomic crystals is observed.

PIEZORESISTANCE OF n-TYPE GERMANIUM. H. Fritzsche, Department of Physics and Institute for the Study of Metals, The University of Chicago, Chicago, Illinois (Received February 18, 1959).

The change of electrical resistance in uniaxial tension has been measured over the range 6°K to 300°K for several single-crystal specimens of germanium doped with arsenic or antimony. The tensile stress was varied from 1×10^{7} to 5×10^{8} dynes/cm^2. Particularly at low temperatures where most of the carriers are bound to impurity centers, the piezoresistance of the conduction band departs strongly from linearity in stress. For the large piezoresistance effects measured with uniaxial stress in the [110] direction, these departures depend in size and magnitude on the kind of donor impurity. It is shown that if the strain-induced shift of the Fermi energy is taken into consideration these effects are to be expected from the electron transfer model, which attributes the large piezoresistance to the strain-induced changes of the electron concentrations in the various conduction band valleys. Theoretical predictions concerning the lowest donor states—a onefold $1s$-like ground state and a higher-lying threefold state—are verified for As in Ge. The energy separation between these two states is $(4.10\pm0.15)\times10^{-3}$ ev for As and at least by an order of magnitude smaller for Sb in Ge. The deformation potential constant (conduction band) for pure shear strain was found to be $E_2=19.2\pm0.4$ ev at 6.6°K. The mobility anisotropy of a valley was found to decrease with decreasing T because of anisotropic scattering by ionized impurities.

SUGGESTION CONCERNING MAGNETIC INTERACTIONS IN SPINELS. D. G. Wickham and J. B. Goodenough, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts (Received April 6, 1959).

The indirect-exchange mechanisms which produce spontaneous magnetization in metal oxides are an optimum if two interacting cations are located on opposite sides of an anion. The coupling rules which have been developed for this case are not applicable to spinels in which the cation-anion-cation angles differ appreciably from 180°. An examination of the d-orbital symmetry of various cations in respect to the crystal lattice leads to several suggestions concerning the magnetic interactions in spinels. Of particular interest are those spinels containing cations with three or fewer d-electrons in the octahedral sites, or four if the symmetry is tetragonal. The properties of several spinels of this kind are considered in the light of the suggestions offered. Direct interactions between octahedral-site cations appear to be possible.

CORRELATION FUNCTION METHOD FOR TRANSPORT PHENOMENA. Hazime Mori,* Metcalf Research Laboratory, Brown University, Providence, Rhode Island (Received February 20, 1959).

An expression for the nonequilibrium density matrix is derived in terms of dynamical fluxes, which leads to a rigorous formulation of the correlation-function method for transport phenomena with nonuniform thermodynamic quantities.

* On leave of absence from Kyushu University, Fukuoka, Japan.

PHASE DIAGRAM OF RUBIDIUM TO 150 000 kg/cm² AND 400°C. F. P. Bundy, Research Laboratory, General Electric Company, Schenectady, New York (Received February 26, 1959).

A room temperature transition was found in rubidium at 107 000 kg/cm². It is characterized by an abrupt increase in electrical resistance of about 12 to 15%. The melting temperature increased with pressure in a normal manner up to about 25 000 kg/cm²; then the rate of rise diminished rapidly until a maximum melting point of about 280°C was reached at 50 000 kg/cm². Beyond this, the melting point decreased with increasing pressure. A triple point at 112 000 kg/cm², 200°C occurred at the junction of the solid I-II line and the melting line. Only electrical resistance type measurements were made. Other transitions might be shown by volume measurements.

ULTRASONIC ATTENUATION IN BISMUTH AT LOW TEMPERATURES. Darrell H. Reneker,* Department of Physics and Institute for the Study of Metals, University of Chicago, Chicago, Illinois (Received February 20, 1959).

The attenuation of ultrasonic waves in bismuth has been measured at frequencies between 12 and 84 Mc/sec for various orientations. The magnetic field dependence of the attenuation at low temperatures exhibits three distinct oscillatory components and a saturation region at fields between 5 and 1600 oersteds. A simple interpretation of the salient features of the observations is presented. In particular, the effective-mass parameters of the electrons have been determined from the periods of the geometric resonance and de Haas–van Alphen oscillations. A method of measuring the maximum Fermi velocity in a given direction is described, and the results of such a measurement are used to determine an independent value of the Fermi energy. Some data on the temperature and frequency dependence of the zero-field attenuation are included.

* Now at Polychemicals Department, E. I. du Pont and Company, Wilmington, Delaware.

CALCULATION OF THE SPECIFIC HEAT OF SOME ALKALI HALIDES. Clark Oliphint, The Rice Institute, Houston, Texas (Received February 19, 1959).

The specific heats of LiF, KCl, and KI have been calculated, using Houston's approximation to find the frequency spectrum. These calculations are compared to measurements of specific heat, to a calculation using Debye's theory, and to a calculation by Briscoe and Squire. The specific heat curves are plotted by Bijl's method.

CRYSTAL STRUCTURE OF THE FERROELECTRIC PHASE OF $(GLYCINE)_3 \cdot H_2SO_4$. S. Hoshino, Y. Okaya, and R. Pepinsky, X-Ray and Crystal Structure Laboratory, Department of Physics, Pennsylvania State University, University Park, Pennsylvania, and Department of Physics, Brookhaven National Laboratory, Upton, New York (Received February 13, 1959).

Ferroelectric $(glycine)_3 \cdot H_2SO_4$ crystallizes at room temperature in the monoclinic system with $a = 9.41_7$ A, $b = 12.64_3$ A, $c = 5.73_6$ A, $\beta = 110°23'$; the space group is $P2_1$, and the polar direction is along the twofold screw axis. Above 47°C the spontaneous polarization disappears as the space group becomes $P2_1/m$. The crystal structure was determined from full three-dimensional x-ray diffraction data, using Cu $K\alpha$ radiation. Out of the three glycine molecules in the crystal, one has the usual zwitter-ion configuration, with the NH_3^+ group out of the plane of the other atoms; the remaining two glycines are mono-protonated, and planar within experimental error, and are designated as glycinium ions. Thus the chemical formula is properly written as

$$(NH_3^+CH_2COO^-) \cdot (NH_3^+CH_2COOH)_2 \cdot SO_4^{--},$$

and the compound is best described by the chemical name glycine diglycinium sulfate. One of

the planar glycinium ions lies near but not in the plane $y=\frac{1}{4}$, which becomes the mirror plane in the high-temperature phase.

The nitrogen atoms form N-H··O hydrogen bonds of the usual strength, whereas a quite strong O-H··O hydrogen bond of a distance of 2.43_8 A is found between the oxygen atom of the carboxyl group of the zwitter-ion glycine and that of the planar glycinium ion which lies near the plane $y=\frac{1}{2}$.

Above the Curie point, at 47°C, mirror symmetry is attained by statistical arrangement of atoms around the mirror planes at $y=\frac{1}{4}$ and $\frac{3}{4}$. The disorder of the glycinium ions near the mirror planes, and the above-mentioned strong O-H··O bond, are of particular importance for the ferroelectric behavior of the crystal.

FUSION CURVES OF FOUR GROUP VIII METALS TO 100 000 ATMOSPHERES. H. M. Strong and F. P. Bundy, Research Laboratory, General Electric Company, Schenectady, New York (Received February 25, 1959).

The fusion curves of Ni, Pt, Rh, and Fe have been experimentally determined to 100 000 atmospheres. At this pressure, the melting points of the pure metals were: Ni, 1670±10°C; Pt, 2070±15°; Rh, 2400±15°; Fe, 1740±10°. The Pt and Rh values were extrapolated by Simon's fusion equation which fitted all of the data quite well and enabled the volume changes at the melting point to be computed. $\Delta V/V_s$ for the four metals were: Ni, 0.06±0.01; Rh, 0.12 ±0.03; Fe, 0.03±0.005. The constants of Simon's equation differed considerably from their theoretical values but a functional relationship appears evident between Simon's exponent c and the Grüneisen constant γ.

ELECTRON SPIN RESONANCE OF NITROGEN DONORS IN DIAMOND. W. V. Smith, P. P. Sorokin, I. L. Gelles, and G. J. Lasher, Research Laboratory, International Business Machines Corporation, Poughkeepsie, New York (Received January 28, 1959; revised manuscript received May 6, 1959).

Electron spin resonance of bound substitutional nitrogen donors in diamond is observed and discussed. The g factor is isotropic at 2.0024 ±0.0005. For a given donor, one of the C-N bond directions is a hyperfine axis with constants $A=40.8$ oersteds, $B=29.2$ oersteds. There are thus four types of donors, equally abundant. A model for the donor wave function is proposed which puts the donor electron principally into an antibonding orbital located on a nitrogen atom and on one of its nearest neighbor carbon atoms. A C-N bond distortion results which can be regarded as a manifestation of the Jahn-Teller effect. A careful search reveals the presence of an additional weak spectrum due to donors on N^{14}-C^{13} pairs. (The isotope C^{13} which has a nuclear spin of $\frac{1}{2}$ has a natural abundance of 1.1%.) The hyperfine constants measured for a C^{13} atom of an N-C pair are $A'=60.8$ oersteds, $B'=25.3$ oersteds. The s and p contributions to all four measured hyperfine constants are separated to give the values:

$$O_N=(8\pi/3)|\psi(0)|_N^2=2.41 \text{ atomic units},$$

$$P_N=\langle[z^2-\tfrac{1}{2}(x^2+y^2)]/r^5\rangle=0.28 \text{ atomic unit},$$

$$O_C=(8\pi/3)|\psi(0)|_C^2=0.78 \text{ atomic unit},$$

$$P_C=\langle[z^2-\tfrac{1}{2}(x^2+y^2)]/r^5\rangle=0.25 \text{ atomic unit}.$$

These are compared with theoretical values obtained by assuming a simple antibonding wave function composed of nitrogen and carbon tetrahedral orbitals. An increase of several percent in the N-C separation along the hyperfine axis is strongly implied by the comparison.

SURFACE STATES IN METALS. G. Bonfiglioli, Istituto Elettrotecnico Nazionale, Turin, Italy, and R. Malvano, Istituto di Fisica dell'Università, Turin, Italy (Received February 17, 1959).

This paper deals with measurements of conductivity modulation of metals by an electric field. The measurements have been performed using a new technique, which permits reaching an accuracy sensibly higher than that obtained in experiments already published. Measurements with Au, Sb, and Bi films have been carried out at different temperatures between about -20 and +80°C. The existence of localized and conducting "surface states" at the metal-dielectric interface seems to be experimentally confirmed.

TOTAL PHOTOELECTRIC CROSS SECTIONS OF Cu, Mo, Ag, Ta, AND Au AT 662 kev. W. F. Titus,* National Bureau of Standards, Washington, D. C. (Received February 24, 1959)

The total photoelectric cross sections of Cu, Mo, Ag, Ta, and Au have been measured at 662

kev. A highly collimated beam of gammas from a Cs^{137} source impinged upon a thin disk of a target material. Photoelectrons from a target were detected by a plastic scintillator subtending very nearly 4π steradians. Pulse-height analysis permitted partial resolution of photoelectric and Compton events. After subtraction of unresolved Compton events and correction for coherent scattering effects, the cross sections were found to be 0.125 ± 0.009, 0.700 ± 0.016, 1.198 ± 0.028, 8.55 ± 0.14, and 11.62 ± 0.16 barns, respectively, in satisfactory agreement with theory.

*Now at Dartmouth College, Hanover, New Hampshire.

ENERGY SPECTRUM OF ELECTRONS EMITTED FROM GASES BOMBARDED BY POSITIVE IONS. David E. Moe* and Otto H. Petsch,† Department of Physics, Western Reserve University, Cleveland, Ohio (Received February 24, 1959).

The energy spectrum of electrons emitted during ionization of gases bombarded with positive ions has been studied for electrons emitted parallel and perpendicular to the incident ion beam. The observed spectra are not strongly dependent upon the direction of electron emission.

*Present address: California State Polytechnic College, San Luis Obispo, California.
†Present address: Marietta College, Marietta, Ohio.

SAUTER THEORY OF THE PHOTOEFFECT. U. Fano, National Bureau of Standards, Washington, D. C.; K. W. McVoy,* Brookhaven National Laboratory, Upton, New York; and James R. Albers,† National Bureau of Standards, Washington, D. C. (Received January 30, 1959).

Results of Sauter are expressed in the form of a transition matrix which determines the photoeffect cross section for arbitrary x-ray polarization and arbitrary initial and final orientations of the electron spin. The structure of the matrix elements accounts for curious properties of the cross section in terms of interference between orbital and spin currents. Expansion of the wave functions into powers of $Z/137$ simplifies the calculation of the transition matrix, reduces it to a special case of the bremsstrahlung theory in Born approximation, and explains discrepancies between results of earlier calculations. Analytical and graphical data are given on the photoemission of polarized electrons by circularly polarized x-rays.

*Now at Brandeis University, Waltham, Massachusetts.
†Now at Institut für Theoretische Physik, Heidelberg, Germany.

HIGH-FREQUENCY LIMIT OF BREMSSTRAHLUNG IN THE SAUTER APPROXIMATION. U. Fano, National Bureau of Standards, Washington, D.C. (Received January 30, 1959).

The expansion in powers of $Z/137$ utilized in the Sauter theory of the photoelectric effect yields a nonzero cross section proportional to Z^3 at the limit of the bremsstrahlung spectrum, and also at the low electron energy limit of the pair-production spectrum. These cross sections are related to the Sauter photoelectric cross section by detailed balancing. The results apply equally when the effects of spin orientations and x-ray polarization are considered.

INTERFERENCE OF ORBITAL AND SPIN CURRENTS IN BREMSSTRAHLUNG AND PHOTOEFFECT. U. Fano, National Bureau of Standards, Washington, D. C.; K. W. McVoy, Brandeis University, Waltham, Massachusetts; and James R. Albers,* National Bureau of Standards, Washington, D. C. (Received January 30, 1959).

The matrix elements of the Born-approximation theory of bremsstrahlung are resolved into sums of terms classified according to whether the radiation interacts with orbital or with spin currents and on the basis of additional spin effects which result from electron motion before and after the emission. Observable features of angular distribution, x-ray polarization, and spin orientation can be interpreted as effects of interference between the separate terms. The results are applicable to corresponding features of the photoeffect.

*Now at Institut für Theoretische Physik, Heidelberg, Germany.

BREMSSTRAHLUNG AND THE PHOTOELECTRIC EFFECT AS INVERSE PROCESSES. Kirk W. McVoy,* Brookhaven National Laboratory, Upton, New York, and U. Fano, National Bureau of Standards, Washington, D. C. (Received January 30, 1959).

The bremsstrahlung matrix element at the short-wavelength limit of the spectrum is calculated to lowest order in $\alpha \equiv Z/137$, for an unscreened Coulomb field. The result, valid for relativistic incoming electrons, is shown to be exactly $\alpha^{-1}m^{-\frac{1}{2}}$ times the complex conjugate of Sauter's relativistic matrix element for the K-shell photoelectric effect. These matrix elements are the leading terms in an expansion of the exact matrix elements in powers of α, and they are found to be derivable from the first two terms of the expansions, in powers of α, of the electron wave functions. In this sense their structure is completely analogous to that of the Bethe-Heitler bremsstrahlung matrix element.

This simple relation between the matrix elements derives from an approximate equality (through first order in α) between the Coulomb wave functions for bound and zero-momentum continuum states, which can be understood as due to the neglect of the Coulomb binding energy, a second-order quantity in α.

Finally, the range of validity of Sauter's approximation is examined in detail. The lower bound of this (energy) range is found to be simply related to the radius of convergence of the expansion of the photoeffect matrix element in powers of α.

* Now at Brandeis University, Waltham, Massachusetts.

ANTISHIELDING AND POLARIZABILITIES IN ALKALI HALIDE GASES. Gerald Burns, International Business Machines Research Laboratory, Poughkeepsie, New York (Received January 20, 1959).

The ionic model that has been used in an attempt to explain eQq/h data in ionic gases and solids is examined, extended, and applied to alkali halide gases. It is shown that the antishielding factor, γ_∞, multiplies the unshielded value of q, $[2c/R^3]$, produced not only by an external charge but by all the external moments, and some of these effects are important in alkali halide gases. In order to estimate the magnitude of the contributions to q of such moments, polarizabilities are calculated that apply to alkali halide internuclear distances. These polarizabilities are often much smaller than those calculated for the free ion. Polarizabilities and γ_∞'s are calculated using both Hartree and Hartree-Fock wave functions and are compared. The values obtained using the Hartree-Fock wave functions are consistently smaller. Some second order calculations of the polarizabilities and antishielding factor are calculated by a direct substitution method. The results indicate that for the alkali halide gas calculations, perturbation theory is applicable to the alkali ions but not to the easily deformable halide ions for the situation considered here. This is probably the reason the ionic model has always yielded poor results for the halide ions. When the ionic model is extended, as described in this paper, and applied to the alkali ions, a set of antishielding factors is found for which there is agreement between theory and experiment or would be if Hartree-Fock wave functions were available to calculate γ_∞. From this model the nuclear quadrupole moment, Q, of Li^7 is found to be -0.016×10^{-24} cm^2.

WAVE FUNCTION FOR THE FREE ELECTRON. I. THE COULOMB POTENTIAL. R. G. Breene, Jr., and Maria C. Nardone, Aersciences Laboratory, Missile and Space Vehicles Department, General Electric Company, Philadelphia, Pennsylvania (Received January 26, 1959).

The wave function for a free electron in the presence of an atom is considered for the case of the Coulomb potential, a potential which ignores both the effects of electron exchange and core polarization. A sample calculation involving the neutral oxygen atom is carried through. From the single determinant wave function for the ^3P ground state of this atom the Coulomb potential is developed, and the important parts of the potential for the s- and d-wave portions of the free-electron wave function are considered. The relevant Schrödinger equations are solved by means of an IBM 704 program which is written so as to be readily adaptable to electrons in the presence of other atoms or ions having electrons through $2p$. In our oxygen example the wave function calculations were carried out for values of the free-electron linear momentum ranging from 0.01 through 0.80 atomic unit.

ELASTIC SCATTERING AND POLARIZATION OF PROTONS BY HELIUM AT 147 AND 66 Mev. A. M. Cormack,* J. N. Palmieri, N. F. Ramsey, and Richard Wilson, Cyclotron Laboratory, Harvard University, Cambridge, Massachusetts (Received March 2, 1959).

Measurements have been made of the polarization and differential cross section in elastic p-α scattering at 147 and 66 Mev, in the laboratory angular ranges of 2° - 165° and 10° - 45°, respectively. These have been compared with recent calculations which relate the scattering amplitudes to nucleon-nucleon results. Because these calculations take into account the angular variation of the nucleon-nucleon amplitudes, better agreement is obtained than heretofore. A comparison of the polarization with that observed in inelastic scattering from several levels of a variety of spin-zero nuclei indicates a strong similarity between the elastic and inelastic data, which can be explained theoretically.

* On leave from the University of Cape Town, Rondebosch, Cape, South Africa. Now at Tufts University, Medford, Massachusetts.

ELASTIC SCATTERING AND CAPTURE OF PROTONS BY C^{14}. D. F. Hebbard, Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California, and D. N. F. Dunbar,* Physics Department, University of Melbourne, Melbourne, Australia (Received March 2, 1959).

The reaction $C^{14}(p,p)$ has been investigated over the energy range from 340 to 690 kev. No wide anomalies are found, but a narrow anomaly at 527 kev has been attributed to d-wave protons forming a state of spin $\frac{3}{2}^+$. The reaction $C^{14}(p,\gamma)$, investigated over the range from 250 to 690 kev, shows a resonance at 261 kev in addition to the three previously known resonances at 351, 527, and 634 kev. Proton and radiative widths are obtained for all these resonances, and limits are placed on the spin assignments. From the data obtained, it is clear that the levels corresponding to the resonances at proton energies of 261, 351, and 527 kev cannot contribute significantly to the scattering or capture of low-energy neutrons by N^{14}. In addition, the level corresponding to the 634-kev resonance cannot be responsible for the whole of the $N^{14}+n$ cross section at low energies, but it may be responsible for part of this cross section. It is suggested that the level at 9.84 Mev is responsible for the remainder of this cross section. A good fit to the neutron elastic scattering cross section is obtained over the neutron energy range from 0 to 600 kev.

* Now at Canberra University College, Canberra, Australia.

ANGULAR CORRELATION MEASUREMENTS IN O^{15}. B. Povh* and D. F. Hebbard, Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California (Received March 2, 1959).

An accurate measurement of the energy of a gamma transition from the 7.56-Mev level in O^{15} discloses that the transition takes place to the 5.19-Mev level in O^{15} rather than to the 5.25-Mev level. Another transition takes place through the 6.15-Mev level. The third known transition occurs through the 6.79-Mev level rather than through the 6.86-Mev level. The angular correlations of cascades from the 7.56-Mev level through the levels at 6.79 Mev, 6.15 Mev, and 5.19 Mev are measured. These results, combined with previous results on these levels, are consistent only with $J^\pi = \frac{3}{2}^+$ and $\frac{3}{2}^-$, respectively, for the 6.79-Mev and 6.15-Mev levels. For the 5.19-Mev level, the present results indicate $J = \frac{1}{2}$, but are consistent also with $J = \frac{3}{2}$, if a suitable mixing ratio of $E2$ to $M1$ radiation is chosen. The preferred assignments are all consistent with the shell-model predictions and with comparisons with the N^{15} level scheme. It is noted that the doublets near 5.2 Mev in O^{15} and N^{15} are reversed in order.

* On leave from The "J. Stefan" Institute, Ljubljana, Yugoslavia.

He^3- AND He^4-INDUCED COULOMB EXCITATION. D. A. Bromley, J. A. Kuehner, and E. Almqvist, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada (Received March 2, 1959).

In order to examine the characteristics of the He^3-induced Coulomb excitation process and the validity of the cross-section ratio technique for the identification of both $E1$ and $E2$ transitions, thick-target radiation yield ratios have been measured for He^3- and He^4-induced Coulomb excitation of each of the 110- and 197-kev levels

of F^{19}, the 446-kev level of Na^{23}, the 160-kev level of Ti^{47}, and the 126-kev level of Mn^{55} at corresponding (equal ξ) energies. For the $E2$ transitions a mean ratio of the He^3- to He^4-induced yields of 0.63 ± 0.02 was found, independent of incident energy in the range 1.0 to 2.5 Mev, in agreement with the calculated value of 0.64 for F^{19} and Na^{23} and of 0.63 for Ti^{47} and Mn^{55}. In the single $E1$ transition (110 kev in F^{19}) studied, the experimental ratios range from 0.76 ± 0.07 at $E_{He^3} = 1.00$ Mev to 0.59 ± 0.11 at $E_{He^3} = 1.75$ Mev. While in accord with the theoretical prediction of 0.76 at the lower energies, the indicated energy dependence of the ratio is suggestive of contributions due to nuclear inelastic scattering of alpha particles. It has been demonstrated that the ratio technique, using He^3 and He^4 ions, provides an unambiguous multipolarity determination provided that inelastic-scattering contributions can be excluded.

NUCLEAR SPINS OF SILVER-104 AND SILVER-106. W. B. Ewbank, L. L. Marino, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee,* Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California (Received March 4, 1959).

The nuclear spins of four neutron-deficient isotopes of silver have been measured by atomic-beam methods. The results are as follows: For 27-min Ag^{104}, $I = 2$; for 1.2-hr Ag^{104}, $I = 5$; for 24-min Ag^{106}, $I = 1$; for 8.3-day Ag^{106}, $I = 6$. Of these, the result for 1.2-hr Ag^{104} has not been reported previously.

*Present address: University of Washington, Seattle, Washington.

SPIN-ORBIT CONTRIBUTIONS TO THE H^3-He^3 MAGNETIC MOMENTS. Jay M. Berger, International Business Machines Research Center, Yorktown Heights, New York (Received February 27, 1959).

The contributions to the magnetic moments of the triton and He^3 from the Signell-Marshak and Gammel-Thaler phenomenological spin-orbit potentials have been calculated using the Pease and Feshbach wave functions. The results indicate that the isotopic spin dependence of the spin-orbit potential should be of the form $(3 + \vec{\tau}_i \cdot \vec{\tau}_j)$ and also that the spin-orbit potential contributions are too small by an order of magnitude to account for the approximately 0.2 nuclear magneton anomalies in the H^3-He^3 magnetic moments.

SINGLE-PARTICLE STATES OF THE NEUTRON FROM GROSS STRUCTURE IN THE PROTON SPECTRA OF (d,p) REACTIONS. J. P. Schiffer, L. L. Lee, Jr., and B. Zeidman, Argonne National Laboratory, Lemont, Illinois (Received February 25, 1959).

Systematic gross-structure peaks have been observed in the proton spectra from (d,p) reactions on nuclei in the region of atomic weight 60. Measurements at deuteron energies of 4, 10, and 21.6 Mev were made with the energy resolution in the proton detectors considerably worse than the known spacing of levels in these nuclei. In all these measurements, the peaks in the proton spectra stayed at a fixed energy of the captured neutron. Angular distributions obtained with 10-Mev deuterons were analyzed in terms of the Butler theory of stripping reactions. It was found that each peak in the proton spectrum corresponded to a specific value of the orbital angular momentum of the captured neutron. The peaks are interpreted as being caused by the shell-model single-particle states of the captured neutron, when these states are smeared out among the many actual levels of the nucleus. Thus the observed gross-structure peaks are believed to correspond to the giant resonances of the complex-potential model of Feshbach, Porter, and Weisskopf. Peaks have been assigned to the $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$, $2d_{5/2}$, $3s_{1/2}$, and $2d_{3/2}$ shell-model states, although all these states could not be identified in every nucleus that was studied. The relative intensities of the peaks are also consistent with this interpretation, except for the $l = 0$ peaks at high excitation energies. Information on the ground-state configurations of the target nuclei has also been obtained from the intensities.

SCATTERING OF HIGH-ENERGY NEUTRONS BY He^4. T. W. Bonner, F. W. Prosser, Jr., and J. Slattery, Rice Institute, Houston, Texas (Received February 24, 1959).

The scattering of neutrons in He^4 has been investigated for neutrons with energies of from 16

to 23.4 Mev with a helium-filled ionization chamber. A pronounced resonance has been found at at a neutron energy of 22.15 ± 0.12 Mev. This resonance corresponds to an excitation energy in He^5 of 16.72 ± 0.10 Mev which is the same excitation energy as that obtained for the maximum in the $T(d,n)He^4$ cross section. The neutron-scattering experiments indicate that the level in He^5 has a width of about 100 kev which is much narrower than the ground state of He^5. This state in He^5 probably has angular momentum and parity of $\frac{3}{2}^+$ and is made up of two neutrons and a proton in the S shell and one proton and one neutron in the P shell. Such a configuration would explain the large deuteron reduced width of the $T(d,n)He^4$ reaction and the small neutron width.

BETA-DECAY ENERGY OF TRITIUM. Fred T. Porter, Argonne National Laboratory, Lemont, Illinois (Received February 20, 1959).

The extrapolated end point from Kurie plots of the tritium beta spectrum between 14 and 18 kev has been measured as 18.61 ± 0.02 kev on the Argonne double-lens beta spectrometer. Composite sources of tritiated estradiol and 10-hr thorium B (Pb^{212}) and its daughters allow calibration at 25 kev (the "A" line) as well as some check on the effect of the source thickness on the "A" line. A review of other measurements shows agreement at a value of 18.6 ± 0.1 kev among mass difference data, average energy determination, proportional counter work, and the present magnetic spectrometer result. Two notable exceptions give lower values, 18.2 and 18.0 kev—one an average energy determination, the other a magnetic spectrometer result. The 18.6-kev decay energy and a half-life of 12.43 years give $ft = 1137 \pm 20$ sec.

PRECISE DETERMINATION OF NUCLEAR REACTION ENERGIES AND MEASUREMENTS OF RESONANCE WIDTHS. R. O. Bondelid and C. A. Kennedy, Nucleonics Division, United States Naval Research Laboratory, Washington, D. C. (Received February 13, 1959).

An electrostatic analyzer with a radius of curvature of 2 meters and a deflection angle of 90° has been constructed and evaluated. It is used to provide an ion beam whose energy is precisely known and highly resolved. The absolute energy calibration is believed to be accurate to $\pm 0.05\%$, and the inherent energy resolution is 0.01% per 0.010 in. of input slit separation. Proton bombarding energies have been determined for (p,γ) reactions on F^{19} at 340.5 ± 0.3 kev, 483.6 ± 0.3 kev, and 872.4 ± 0.4 kev; Al^{27} at 992.4 ± 0.5 kev; Ni^{58} at 1424.1 ± 0.7 kev and 1843.7 ± 0.9 kev; and C^{13} at 1747.6 ± 0.9 kev. Resonance widths have been measured for these reactions. They are 2.4 ± 0.3 kev, 0.9 ± 0.1 kev, 4.5 ± 0.3 kev, 100 ± 50 ev, 50 ± 50 ev, 100 ± 50 ev, and 75 ± 50 ev, respectively. The (p,n) thresholds have been determined for Li^7 at 1881.2 ± 0.9 kev and for C^{13} at 3237.2 ± 1.6 kev.

ELASTIC SCATTERING OF PROTONS BY VANADIUM, CHROMIUM, IRON, AND COBALT. C. A. Preskitt* and W. P. Alford, Department of Physics and Astronomy, University of Rochester, Rochester, New York (Received February 24, 1959).

A total of thirty-three angular distributions of elastically scattered protons have been measured in the energy range from 3.49 to 6.42 Mev with the targets V, Cr, Fe, and Co. It was observed that the angular distributions measured with V and Co have similar shapes at all energies. Likewise the angular distributions with Cr and Fe are similar, but qualitatively different from those with V and Co. Using the optical model, it has been possible to obtain fits to some of the data for V and Co, but the large cross section at large angles prevents an adequate fit to the Cr and Fe data. Calculations are presented which indicate that this failure of the optical model is due to the presence of compound elastic scattering from Cr and Fe.

* Present address: Oak Ridge National Laboratory, Oak Ridge, Tennesse.

MAGNETIC MOMENTS OF STRONGLY DEFORMED ODD-ODD NUCLEI. W. M. Hooke,* Palmer Physical Laboratory, Princeton University, Princeton, New Jersey (Received February 19, 1959).

The strong-coupling magnetic moment relation for odd-odd nuclei is evaluated with the use of Nilsson wave functions for finite values of core distortion. The theoretical predictions are compared with all of the data available on odd-odd nuclei in the strong-coupling region. There is

no evidence for appreciable error having been introduced by the assumption of no interaction between the odd proton and odd neutron.

*Now at Forrestal Research Center, Princeton University, Princeton, New Jersey.

DECAY OF Tb^{156}(5-DAY). Shimon Ofer,* Brookhaven National Laboratory, Upton, New York (Received February 16, 1959).

Radioactive Tb^{156} (~5-day) was produced by the bombardment of Eu^{153} with α particles. It was found to decay by K capture to Gd^{156}. A decay scheme has been proposed which includes the following excited states of Gd^{156}: 89 kev (2+), 289 kev (4+), 581 kev (6+), 1134 kev (2+), 1229 kev (3+), 1489 kev (4+), 1604 kev, 1904 kev (3), and 2024 kev (4-). The assignment of spin of levels and multipolarities of gamma-ray transitions are based on the results of measurements of conversion coefficients and gamma-gamma angular correlations. A value of $(1.5\pm0.3)\times10^{-10}$ sec was found for the mean life of the 289-kev level of Gd^{156}. The level scheme is discussed in the light of the unified model. The results support the suggestion that the 1134-kev and 1229-kev levels should be interpreted as collective vibrational levels.

*On leave from the Hebrew University, Jerusalem, Israel.

DECAY OF $_{64}Gd^{161}$(3.73-MIN). L. C. Schmid and S. B. Burson, Argonne National Laboratory, Lemont, Illinois, and J. M. Cork, University of Michigan, Ann Arbor, Michigan (Received December 23, 1958).

The decay of $_{64}Gd^{161}$(3.73-min) is characterized by beta emission to excited states in $_{65}Tb^{161}$. This activity has been investigated by means of the Argonne 256-channel scintillation coincidence spectrometer and photographic internal-conversion-electron spectrographs. Sources were prepared by neutron irradiation of Gd, enriched in Gd^{160}, in the Argonne reactor, CP-5. The presence of three beta-ray branches is deduced; two of these were observed experimentally by means of absorption methods. Fourteen gamma rays are reported. These radiations are fitted into a decay scheme which indicates excited states in Tb^{161} at 56.6, 134.0, 315.3, 417.6, 480.6, and 586.1 kev. A rotational band, based on the ground state and including the first two excited states, is indicated. Spin and parity assignments are also suggested for the third and fourth excited states.

DECAY OF $_{50}Sn^{113}$(112-DAY) AND $_{49}In^{113m}$(1.73-HR). S. B. Burson, H. A. Grench, and L. C. Schmid, Argonne National Laboratory, Lemont, Illinois (Received January 8, 1959).

Samples of $_{50}Sn^{113}$(112-day) were produced by neutron irradiation of tin enriched in Sn^{112}. The gamma rays were studied by scintillation methods using the Argonne 256-channel analyzer; the internal-conversion electrons were investigated by means of a 180° β-ray spectrometer. In addition to the well-established 393-kev gamma ray, a gamma ray of 255 kev was found. Studies of all the tin radioisotopes showed the latter to be in the Sn^{113} activity. Energy levels in In^{113} at 393 and 648 kev, the latter having spin 1/2 or 3/2, are indicated.

DECAY OF $_{62}Sm^{155}$(23.5-MIN). L. C. Schmid and S. B. Burson, Argonne National Laboratory, Lemont, Illinois (Received January 9, 1959).

The decay of Sm^{155}(23.5-min) is characterized by beta emission to excited states in Eu^{155}. This activity was studied by means of the Argonne 256-channel scintillation coincidence spectrometer. Sources were prepared by neutron irradiation of samarium oxide, enriched in Sm^{154}, in the Argonne reactor CP-5. Three gamma-ray transitions and two beta-ray branches are reported. These radiations are fitted into a decay scheme which indicates the presence of excited states in Eu^{155} at 105 and 246 kev. The total decay energy is found to be 1.8 ± 0.1 Mev. Possible spin and parity assignments for each of the levels are discussed.

DECAY OF $_{60}Nd^{151}$(12-MIN). L. C. Schmid and S. B. Burson, Argonne National Laboratory, Lemont, Illinois (Received January 19, 1959).

The decay of Nd^{151}(12-min) is characterized by beta emission to excited states in Pm^{151}. This activity has been investigated by means of the Argonne 256-channel scintillation coincidence spectrometer and photographic internal-con-

version-electron spectrographs. Sources were prepared by neutron irradiation of neodymium oxide, enriched in Nd^{150}, in the Argonne reactor *CP*-5. The presence of six beta-ray branches is deduced; four of these were observed experimentally by means of absorption methods. Thirty gamma-ray transitions are reported. Twenty-seven of these and six beta-ray groups are fitted into a decay scheme which indicates the presence of excited states in Pm^{151} at 0.1172, 0.2560, 0.4265, 0.5336, 0.852, 0.937, 1.12, 1.29, 1.63, 1.87, and 2.17 Mev. The total energy difference between the Nd^{151} parent and the Pm^{151} ground state is found to be (2.4 ± 0.1) Mev. The low-lying levels in Pm^{151} are discussed with particular reference to the possible existence of a rotational series based on the ground state.

NUCLEAR STATES IN THE RaE β DECAY. Neal Newby, Jr., and E. J. Konopinski, Physics Department, Indiana University, Bloomington, Indiana (Received January 8, 1959).

It is shown that the β-transforming neutron of Bi^{210} most probably has an $i_{11/2}$ character, despite a $g_{9/2}$ character of the ground-state neutron in Pb^{209}. This makes a critical difference to the RaE spectrum parameter $\xi = i\langle\vec{r}\rangle/\langle\vec{\sigma}\times\vec{r}\rangle$, yielding $\xi \approx +1$ rather than $\xi \approx -1/10$. The effect of configuration mixing is also investigated but does not affect ξ appreciably.

To arrive at the above conclusions, it is necessary to show that the neutron-proton attraction in the $(h_{9/2}\, i_{11/2})_1$ state is the large amount, 840 kev, greater than in the $(h_{9/2}\, g_{9/2})_0$ state. The resulting shell-model problem has interest independent of the β-theory application which was the primary objective of this work. True and Ford had found that two neutrons extra to the doubly-magic core, Pb^{208}, as against nucleons deep in the core matter, interact with about the same strength and range of force as do two free nucleons. The problem here checks the extension of that important finding to neutron-proton and proton-proton pairs. The force strength is consequently not used as an adjustable parameter, as it has been in previous approaches to such problems.

The True-Ford problem involved only singlet, central forces between like nucleons in an essential way. The RaE daughter, Po^{210}, investigated here, has only Coulomb repulsion superposed. The resultant comparison with experiments is about as good as that obtained by True and Ford.

The extension to the neutron-proton pair of Bi^{210} is far more complex, since triplet forces, an exchange character, and noncentral forces may now come into play. We find that the finite-range, central forces alone cannot give substantially more attraction in the $(h_{9/2}\, i_{11/2})_1$ state than in $(h_{9/2}\, g_{9/2})_0$. Even using the strength as a parameter cannot help significantly. However, the tensor forces produce attraction in the former and repulsion in the latter state. Hence, the two-body forces must be imitated even in this detail in order to yield an explanation of the RaE level scheme. This is unfortunate for quantitative results, because the strength of the two-body tensor force seems never to have been determined unambiguously for potentials without cores.

Our final conclusion is that the two-body neutron-proton force may be well represented by 0-range forces of the same volume energy as found experimentally. Tensor effects vanish identically in this limit and so an unambiguous representation of the strength can be obtained. The results for the relative positions of the $J=0$ and 1 states, used as the test above, now turn out in almost perfect agreement with the observations. Configuration mixing plays a role in this result, and, in consequence, the work includes a generalization of DeShalit's formulas, for the interaction energies with 0-range forces, to nondiagonal matrix elements.

ANALYSIS OF ANGULAR DISTRIBUTIONS IN THE REACTION $B^{11}(\alpha, p)C^{14}$. L. L. Lee, Jr., and J. P. Schiffer, Argonne National Laboratory, Lemont, Illinois (Received December 19, 1958).

Angular distributions of protons from the $B^{11}(\alpha, p)C^{14}$ reaction have been measured with alpha-particle energies ranging from 2.0 to 3.7 Mev. Eight resonances in the reaction have been observed, corresponding to states in N^{15} in the range from 12.50- to 13.60-Mev excitation. Analysis in terms of the compound nucleus formalism has yielded spin and parity assignments for the six most prominent resonances.

NUMERICAL EVALUATION OF DEUTERON STRIPPING CROSS SECTIONS AND POLARIZATIONS. W. Tobocman, The Rice Institute, Houston, Texas (Received October 2, 1958).

The distorted-wave Born approximation is applied to deuteron stripping reactions. Optical

potentials with rounded edges are used to distort the wave functions used in our calculations. It is found possible to get a fair fit to the (d,p) cross section in four cases and to the (d,p) polarization in one case with this treatment without introducing a cutoff.

INVESTIGATION OF HEAVY NUCLEI AND α PARTICLES BETWEEN 7 Bev AND 100 Bev PER NUCLEON. I. INTERACTION MEAN FREE PATHS AND FRAGMENTATION PROBABILITIES. E. Lohrmann and M. W. Teucher, Department of Physics, University of Chicago, Chicago, Illinois (Received March 2, 1959).

In a stack of nuclear emulsion exposed to the cosmic radiation near the geomagnetic equator, 540 tracks of heavy nuclei were located in a systematic scan and followed along the track. Twenty-two interactions of light ($3 \leq Z \leq 5$), 218 of medium ($6 \leq Z \leq 9$), and 99 of heavy ($Z \geq 10$) nuclei have been found. The average energy of the nuclei in this experiment was about 20 Bev per nucleon. The interaction mean free paths for all charge groups are in reasonably good agreement with results obtained at lower energies, indicating that the mean free path is independent of energy within the limits of error. In addition, all the α particles originating in fragmentations of heavy nuclei have been followed. The mean free path of α particles resulting from fragmentations is again in agreement with results obtained at lower energies. The same is true for the fragmentation probabilities.

Fragmentation probabilities in hydrogen are given and their significance is discussed.

INVESTIGATION OF HEAVY NUCLEI AND α PARTICLES BETWEEN 7 Bev AND 100 Bev PER NUCLEON. II. FRAGMENTATIONS AND MESON PRODUCTION BY HEAVY PRIMARIES AND α PARTICLES. P. L. Jain,* E. Lohrmann, and M. W. Teucher, Department of Physics, University of Chicago, Chicago, Illinois (Received March 2, 1959).

Three hundred and seventeen heavy nuclei and 175 α-particle interactions of more than 7 Bev/nucleon have been found in a systematic way and analyzed. We obtained average values and fluctuations of the individual values for the energy of heavy nuclei, as measured by the opening angle of their fragments, by comparing with the energy found by scattering measurements. At an average energy of 10 Bev/nucleon and 40 Bev/nucleon the average number of charged mesons produced by α-particle interactions with emulsion nuclei was found to be 4.6 and 8.2, respectively. About one half of the nucleons of the α particle participate in the collision. The meson multiplicities per participating nucleon agree for proton and α-particle collisions at 10 Bev/nucleon.

We measured the angular distribution of the shower particles emitted from the interactions. We calculated the energy of the interactions from the angular distribution by using the median-angle formula or equivalent formulas, based on the "meson spectrum independent" approximation. These methods overestimate the true primary energy on the average by a factor of 2 (for interactions with less than 5 heavily ionizing prongs). This is due to the relatively large proportion of slow mesons in the center-of-mass system. The distribution of primary energy as obtained by this method around the true value is shown for two groups having average energies of 10 Bev/nucleon and 40 Bev/nucleon. Equivalent results are given for the heavy-nuclei interactions.

The average number of mesons produced in collisions between heavy nuclei and emulsion nuclei at an average energy of 20 Bev/nucleon is given. It increases with the charge of the incident nucleus in agreement with a crude geometrical model.

* On leave of absence from the University of Buffalo, Buffalo, New York.

ENERGY SPECTRUM OF THE HEAVY NUCLEI IN THE COSMIC RADIATION BETWEEN 7 AND 100 Bev/NUCLEON. P. L. Jain,* E. Lohrmann, and M. W. Teucher, Department of Physics, University of Chicago, Chicago, Illinois (Received March 2, 1959).

The energy spectrum of the heavy nuclei of the cosmic radiation was determined between 7 Bev/nucleon and 100 Bev/nucleon. The distributions for the M ($6 \leq Z \leq 9$) and H ($Z \geq 10$) charge groups agree with one another within the limits of error. Combining both charge groups, the integral spectrum is of the form $N(>E) \sim E^{-1.6 \pm 0.15}$ (where E is total energy/nucleon). Flux values for nuclei of the M, H, and VH ($Z \geq 20$) charge groups at the geomagnetic equator are given.

Comparing these results with flux values obtained at high latitudes, it is concluded that a power spectrum of the form $E^{-1.6}$ fits all three charge groups within the limits of error between 2.5 Bev/nucleon and 7 Bev/nucleon. From the observation of α-particle showers of very high energy, it is concluded that under certain assumptions the integral spectrum of α particles can be represented by $N(>E)\propto E^{n}$, where $n=-1.58^{+0.21}_{-0.18}$, for energies ≤ 1500 Bev/nucleon.

*On leave of absence from the University of Buffalo, Buffalo, New York.

RADIATIVE MUON CAPTURE. Jeremy Bernstein, Institute for Advanced Study, Princeton, New Jersey (Received March 6, 1959).

The theory of radiative muon capture is developed. The discussion includes both parity-conserving and parity-nonconserving effects. The Gell-Mann weak magnetic term and the induced pseudoscalar are included, along with comparable relativistic effects in the nucleons. The theory is applied to light nuclei and especially to the radiative Godfrey reaction $\mu^{-}+{}_{6}C^{12}\rightarrow\nu+\gamma+{}_{5}B^{12}$. An experiment to detect the induced pseudoscalar directly is proposed.

SPALLATION OF BISMUTH BY 380-Mev PROTONS. E. T. Hunter and J. M. Miller, Chemistry Department, Columbia University, New York, New York (Received March 5, 1959).

Bismuth was bombarded by the 380-Mev proton beam of the Nevis cyclotron to determine production cross sections of various spallation products. Products isolated and assayed were radioactive isotopes of polonium, bismuth, lead, thallium, mercury, gold, and platinum. Each of these elements was separated from the bismuth targets, carefully purified, and counted using a NaI(Tl) crystal scintillation counter having 4π geometry and $99_{-4}^{+1}\%$ efficiency for photons between 20 and 100 kev.

A mass-yield curve was constructed from these results and compared to the mass-yield curve constructed from available Monte Carlo calculations. The calculated data fit the experimental data quite well for products within about 20 mass number units of the target. A lower limit to the total spallation cross section of 1.14 ± 0.05 barns was obtained.

STRUCTURE OF THE VERTEX FUNCTION. Stanley Deser,* Walter Gilbert, and E. C. G. Sudarshan,† Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts (Received October 15, 1958; revised manuscript received April 6, 1959).

An integral representation, as a function of invariants, is found for the Fourier transform of the matrix element between the vacuum and a one-particle state of the retarded commutator of two currents. A special case is a spectral representation for the vertex as a function of momentum transfer. The threshold in this representation is lower than that found in the usual perturbation theory.

*Now at Brandeis University, Waltham, Massachusetts.
†On leave of absence from Tata Institute of Fundamental Research, Bombay, India.

EUCLIDEAN QUANTUM ELECTRODYNAMICS. Julian Schwinger, Harvard University, Cambridge, Massachusetts (Received March 2, 1959).

Quantum electrodynamics is transcribed into a Euclidean metric. A review is presented of the quantum action principle approach to quantization, with its automatic emphasis on the dynamical variables associated with the physical degrees of freedom. Green's functions of the radiation gauge are defined, and then characterized by differential equations and boundary conditions. These Green's functions are of direct physical significance but involve a distinguished timelike direction. A gauge transformation is then performed to eliminate this dependence, introducing thereby the Green's functions of the Lorentz gauge, which lack immediate physical interpretation. The latter functions are now primarily defined by differential equations and boundary conditions, and form the basis for the analytic extension which is the change from space-time to Euclidean metric. Some properties of anticommuting matrices are discussed in relation to this metric transformation. Real Euclidean Green's functions are defined by correspondence with the Lorentz-gauge functions and the appropriate differential equations obtained. Invariance properties of the Euclidean functions are discussed. The individual Euclidean Green's functions are given an operator construction and then combined into a generating Green's functional which is interpreted as the wave function, in a

canonical field representation, of a state characterized by the Euclidean action operator. Differential operator realizations and some other benefits of a canonical variable description are exhibited.

FORMAL THEORY OF SCATTERING IN THE QUANTUM FIELD THEORY. Smio Tani, Department of Physics, Case Institute of Technology,* Cleveland, Ohio (Received March 2, 1959).

The advantages of the exponential form of the transformation function are exploited. It is shown how to define the representation in which all effects of the self-field of physical particles on themselves are eliminated while the remainder is presented in the form of an effective velocity-dependent potential among them. One can speak of the transformation function which transforms eigenfunctions of the free-particle Hamiltonian into eigenfunctions of the total Hamiltonian: the paradox, which has been pointed out by Van Hove and further studied by Haag with regards to the existence of such a transformation function in quantum field theory, can be circumvented by considering the exponent as its representative. This exponent has a Lorentz-invariant representation. The exponent of the S matrix is related in a very simple manner to the exponent of the transformation function over a finite interval of time. The asymptotic condition as used in the quantum field theory is also analyzed from our viewpoint.

*On leave of absence from Tokyo University of Education, Tokyo, Japan.

SOME CONSEQUENCES OF SYMMETRIES OF THE STRONG INTERACTIONS. G. Feinberg and R. E. Behrends, Brookhaven National Laboratory, Upton, New York (Received March 5, 1959).

The consequences for the electromagnetic interactions of strange particles of some proposed symmetries of the strong interactions are discussed. A minimal electromagnetic coupling is assumed. It is shown that if the interactions with both π and K mesons of the nucleon and cascade particle are identical, if one neglects the n-Ξ mass difference, and if charge independence is satisfied, then the electromagnetic form factors of the Λ^0 and Σ^0, and in particular their magnetic moments, vanish. This is independent of any assumed relation between the Λ and Σ interactions, such as global symmetry. It is also shown that the same conditions, together with charge conjugation invariance, imply a generalized form of the Pais-Jost-Pugh theorem about processes involving only meson or photon external lines. If there is still more symmetry for the strong interactions, as in the case where the π interactions are globally symmetric and the K interactions also have this doublet structure, it is shown that the K^0 acts as a completely neutral particle insofar as electromagnetic interactions are concerned.

STRUCTURE OF THE ELECTROMAGNETIC FIELD. Bruno Bertotti, Institute for Advanced Study, Princeton, New Jersey (Received March 4, 1959).

The structure of a curved space-time in which a source-free electromagnetic field is present is studied according to the "already unified field theory" of Misner and Wheeler, and the geometrical meaning of the differential conditions imposed on the Ricci tensor is established. Four independent equations equivalent to the algebraic conditions are stated, and the case of a null electromagnetic field is also clarified.

ANTICOMMUTATOR FOR A NONLINEAR FIELD THEORY. F. L. Scarf, CERN, Geneva, Switzerland (Received February 26, 1959).

The anticommutator for the Thirring model is computed by ordering the operator $\psi(x)\psi^*(x')$ and evaluating its renormalized vacuum expectation value. The infrared divergence is defined by introducing an ad hoc cutoff. The final expression does not agree with the approximations obtained by using perturbation theory or by using expansion over intermediate states (with the same cutoff). It is also found that Heisenberg's procedures cannot be applied to this two-dimensional problem.

HAAG'S THEOREM AND CLOTHED OPERATORS. O. W. Greenberg, Air Force Cambridge Research Center, Bedford, Massachusetts (Received March 2, 1959).

Haag's theorem is proved. This theorem states—essentially—that a given relativistic field which,